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THE PERFORMANCE OF STAIRWAYS IN EARTHQUAKES

by

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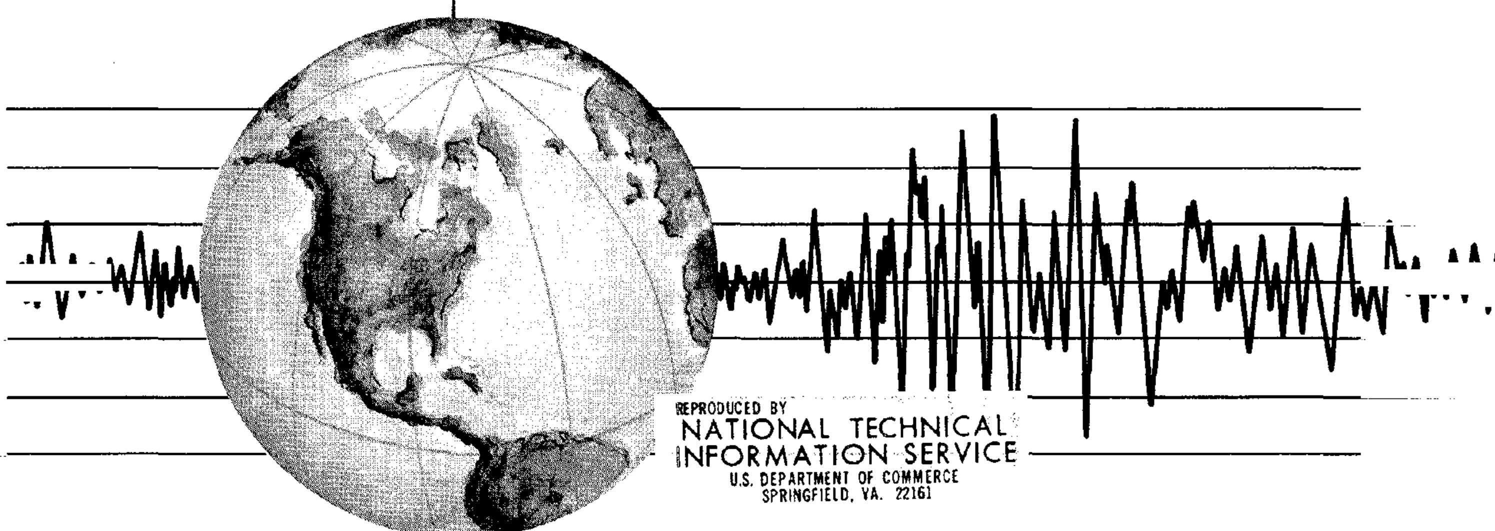
Report to the National Science Foundation



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This project initiates the study of the performance of stairways in earthquakes. The past seismic performance of stairways is reviewed and classified by damage type. Relevant provisions of U.S. and foreign building codes are presented and a model code for stairways is outlined. Current practices in architectural design, structural engineering design and analysis, and building construction are reviewed, design philosophies and strategies are delineated, and recommendations are made. General conclusions are drawn and areas for further study and research are identified.

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THE PERFORMANCE OF STAIRWAYS IN EARTHQUAKES

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ABSTRACT

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The project on the seismic performance of stairways reported herein was conducted as part of a larger research project, "Safety Evaluation of Buildings Exposed to Earthquakes and Other Catastrophic Environmental Hazards," under study at the University of California at Berkeley. Financial support has been provided by the National Science Foundation under Grant No. PFR-76-82384.

Valuable insights concerning the practice of architecture, structural engineering, and building construction were provided by professionals in the San Francisco Bay Area: Lt. Walter Baine (San Francisco Fire Department), Pirooz Barar (Structural Engineer, Skidmore, Owings & Merrill), Byron Cederwall (C.E. Toland & Son, Metal Fabricators), Henry J. Degenkolb (Structural Engineer, H. J. Degenkolb & Associates), Eric Elsesser (Structural Engineer, Forell-Elsesser Engineers), Joseph Esherick (Architect, Esherick, Homsey, Dodge & Davis), John L. Fisher (Architect, Skidmore, Owings & Merrill), Sigmund A. Freeman (Structural Engineer, URS/Blume Engineers), Richard C. Hein (Architect, Anshen & Allen), William Holmes (Structural Engineer, Rutherford & Chekene), Daniel Hom (Structural Engineer, Bureau of Building Inspection, Department of Public Works, City and County of San Francisco), Henry J. Lagorio (Professor of Architecture, University of California, Berkeley), John Raeber (Architect, M. Arthur Gensler Jr. & Associates), Daniel Shapiro (Structural Engineer, Shapiro, Okino, Hom & Associates), Roland Sharpe (Applied Technology Council), Karl V. Steinbrugge (Professor Emeritus of Structural Design, University of California, Berkeley). They are in no way responsible for the authors' interpretations of the conversations.

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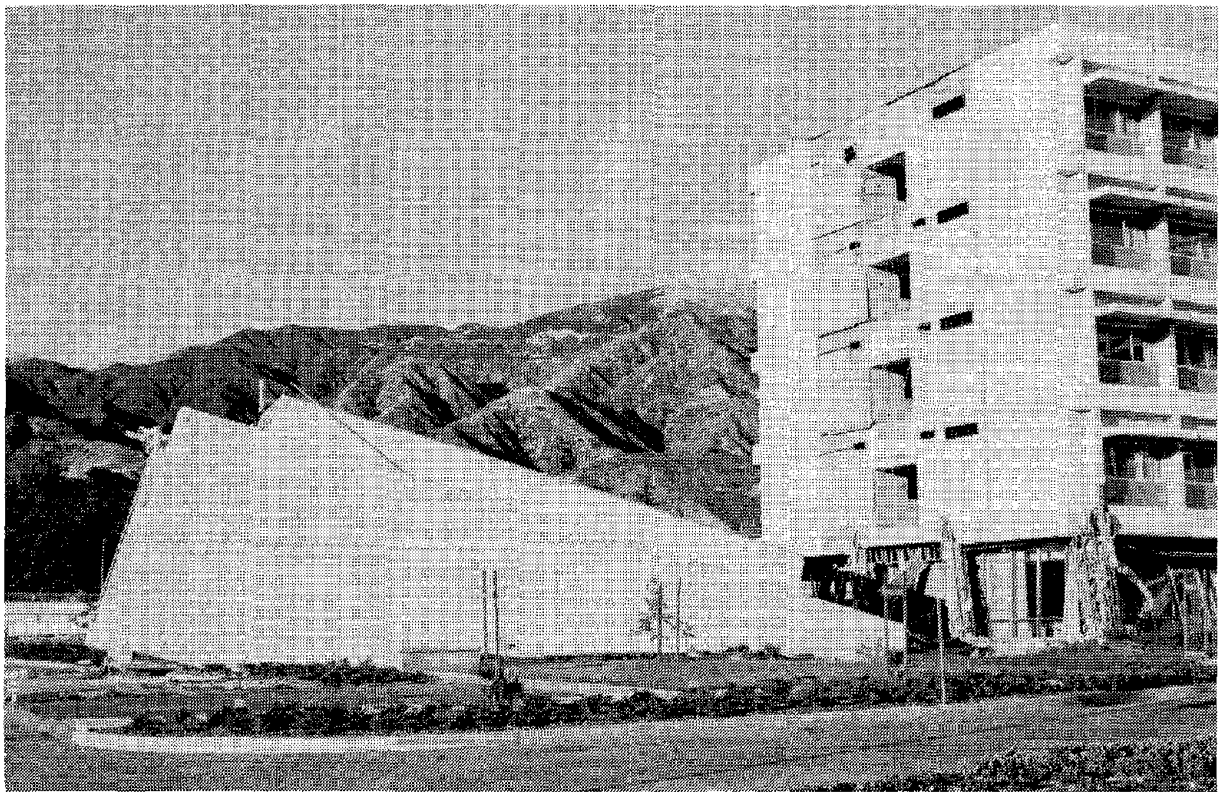


Fig. 1.1 Overturned stair tower, Olive View Hospital, 1971 San Fernando Earthquake. (Photo courtesy of Paul C. Jennings.)

1. INTRODUCTION

Stairways, the primary vertical emergency exit routes in multi-story buildings, are critically important for egress and access during earthquakes and fires. Yet past earthquakes have demonstrated the susceptibility of stairways to damage from seismic shaking. Damaged stairways have delayed evacuation of buildings, impeded efforts by rescuers and fire fighters, complicated salvage and restoration operations, and even resulted in deaths and serious injuries. The need to evacuate a building quickly may arise from an imminent secondary hazard such as fire, explosion, or inundation from dam break, landslide, tsunami, or seiche. Although elevators are the customary vertical transport for buildings over two or three stories, they may not be operational following an earthquake due to electrical or mechanical damage, counterweight derailment, or activation of a seismic detection safety device. Thus, stairways must remain usable after moderate or severe ground shaking so that multi-story buildings may continue their functions.

This problem has been recognized by many experts:

> Emergency access from buildings needs to be protected....Stairs are often severely damaged in earthquakes. That is in their nature....To remain functional stairs must not merely retain their structural integrity, but also must remain clear of debris. (Berg & Degenkolb, 1973)

> Local practice...often allows stairs to act as weak diagonal braces between floors, increasing potential life and property hazards in flexibly framed high-rise buildings. With elevators normally out of service after an earthquake, and this type of stair shattered in a flexibly framed building, then the ability to rescue, evacuate, and/or fight fire in the upper stories of high-rise buildings is seriously reduced. (Steinbrugge, 1970)

> ...there are critical systems within most buildings that are needed during and after an earthquake so as to help provide for public safety. These include emergency lighting, fire sprinkler systems, exit sign illumination, and exit stairways. (Goldberg & Rukos, 1980)

As structural design and construction techniques have improved with new knowledge of seismic effects, a greater proportion of property loss from earthquakes has been in the commonly-called nonstructural and secondary structural components rather than in primary structural systems. Components of stairways, including stair enclosures running the height of the building, doorways and lighting, have been damaged while the primary structure has shown little or no distress. This type of damage has been a recurring problem even in cases of moderate earthquake ground motions.

> The need for damage control measures is strongly supported by evidence from earthquake damage which clearly indicates that non-structural damage may involve a high degree of life hazard. Examples are failures of exterior pre-cast concrete panels, masonry infilling walls and partitions, particularly around stairs and means of egress. (Glogau, 1977)
>
> Stairways and elevators must be designed to remain functional during and after an earthquake. Stairs and doors into stairways and elevators must be designed to permit interstory movements. If the doors will not open after an earthquake, the stairway or elevator is useless. In most buildings, because of fire exit requirements, the walls enclosing elevators and stairways are made of concrete, masonry, or other rigid materials. Such walls, unless they are designed as part of the lateral force resisting system, should not be secured to the main structure without provisions to allow building movement. (Council on Tall Buildings, Group SC, 1980)

Yet the performance of stairways and the effects of damage have been given scant attention in theory, research, and professional practice. Despite architects and engineers' observations of severe stairway damage in every major earthquake, the nature of the interactions of stairways and structures has not been carefully studied. Few recommendations have been made for specific improvements to the seismic resistance of stairways.

In view of this lack of attention to the problem of improving the performance of stairways and their effects on the overall behavior of buildings, it was desirable to initiate this project as part of the general problem, "Safety Evaluation of Buildings Exposed to Earthquakes and Other Catastrophic

Environmental Hazards," which has been under study at the University of California at Berkeley for several years.

1.1 Research Objectives

This project initiated a study of the seismic behavior and performance of exit path stairway systems in multi-story engineered buildings. The principal concerns were the past performance of stairways in earthquakes; published regulations and recommendations for planning, design and construction of stairways; and current practices in architecture, structural engineering, and building construction.

Research objectives were:

(a) to review the past performance of stairways, as evidenced by post-earthquake damage studies, photographs, and engineering reports; to classify characteristic types of stairway damage; to review the effects of stairway damage on evacuation and emergency access;

(b) to review existing building code regulations for stairways in seismic regions; to identify typical exit stairway configurations and components; to identify potential stairway-structure interaction concerns; to review and evaluate current practice of stairway design, analysis and construction;

(c) to consolidate and evaluate this information; to formulate tentative guidelines for planning and design of stairways to improve seismic performance, based on the current state of knowledge; to formulate recommendations for research and development to advance the state of knowledge.

1.2 Methodology

The research project involved consultations with design professionals practicing in architecture, engineering, and construction. Their names are mentioned in the "Acknowledgments" section of this report. Due to project limitations, these contacts were made only in the San Francisco Bay Area. An extensive search was conducted of published materials, engineering reports, earthquake damage studies, journals, conference proceedings, manuals and handbooks, building codes, proposed seismic regulations, photographs and drawings, related to the design and performance of stairways. Major sources were the libraries of the University of California at Berkeley, the Earthquake Engineering Research Center at Richmond, Stanford University at Stanford, and the Earthquake Engineering Research Library at the California Institute of Technology at Pasadena, California.

1.3 Stairway Components and Definitions

A typical stairway system in a multi-story building contains a variety of components.

(a) Stair Structural Components

Stairway or staircase: a flight of stairs, or a series of such flights, including supports, handrails, and framework; the structure containing a flight of stairs
Stair: a series of steps, or flights of steps, connected by landings, which permits passage between two or more levels or floors
Flight: a continuous series of steps with no intermediate landing
Step: a single unit of level change consisting of one tread and one riser
Tread: the horizontal part of a step
Riser: the vertical face of a step
Landing: the horizontal platform at the end of a stair flight or between two flights of stairs
Stair string or stringer: an inclined member which supports the steps
Winder: a tread with one end wider than the other

(b) Enclosure Components

Stairwell or stair core: a vertical shaft containing a stairway
Structural wall
Nonstructural wall
Ceiling
Door & frame
Window & frame
Fire-resistive materials

(c) Architectural Components

Tread, riser and/or landing surfaces
Wall, ceiling and/or soffit finishes
Door hardware
Window hardware
Guardrails, handrails, posts & balusters
Acoustic materials
Signs & numbers

(d) Mechanical Support Systems

Equipment, controls, ducts & pipes
Ventilation systems
Pressurization systems
Wet & dry standpipes

(e) Electrical Support Systems

Equipment, controls & conduit
Service lighting
Emergency lighting
Alarm systems
Communication systems

(f) Incidental Components

Building service ducts & piping
Seismic separation joints

Thus, the stairway system is a complex assembly of numerous components, designed for normal service and emergency functions, and linked by connections and attachments. Most multi-story buildings contain two or more distinctly separate enclosed stairway systems to satisfy emergency exit requirements. There may also be open monumental staircases, fire escapes, and other service stairs.

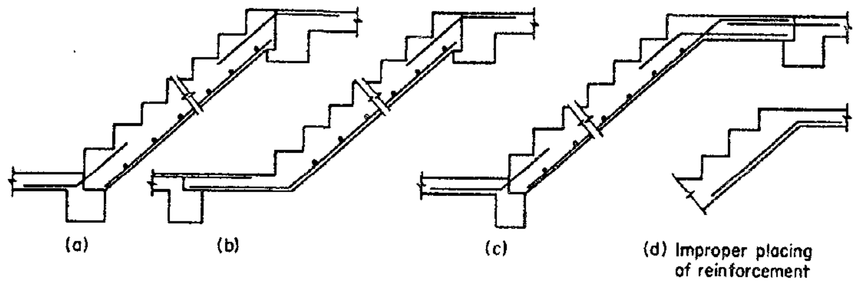
1.4 Conventional Stairway Construction

In multi-story engineered buildings, commonly constructed of structural steel, reinforced concrete, or reinforced masonry, the stairways are designed for a variety of uses. A monumental staircase connecting the main floor with another level may be an important architectural feature which serves a large number of pedestrians. Other public stairways designed for general use, typical in lowrise buildings, may not be as elaborate. Service stairs within fire-resistive enclosures are primarily for emergency egress in high-rise buildings where elevators are the main vertical transport. Industrial stairs can be purely functional. Stairway design is influenced by the degree of visibility, the expected number of users and frequency of use, and specific code requirements governing dimensions and characteristics.

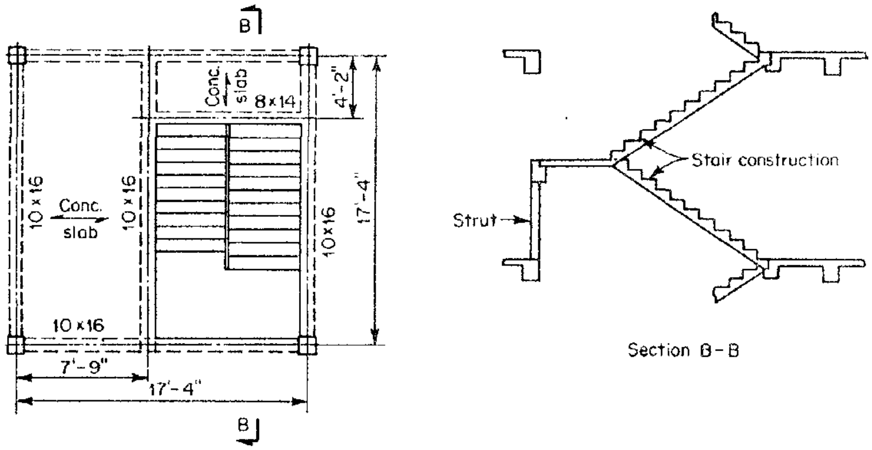
Stairways are comprised of stair flights formed from supported series of steps. The steps may be supported by stringers or walls at both ends, at only one end as single cantilevers, or centrally as double cantilevers. The steps may be supported by an inclined slab, being attached to or monolithically cast with the slab forming a stair flight with a planar undersurface, called a "slab stair." Or the steps and risers may be made from a folded plate with parallel upper and lower profiles, called a "sawtooth" or "slabless" stair flight.

The stair flights may be supported continuously, at their sides, or at their ends by the floors and landing platforms. Intermediate landings may be supported by loadbearing walls at their sides, ends or in the center between flights, by columns at two or more corners or at the center, by beams under the platform, suspended from the floor structure above by hanger rods, supported from below by struts, or enclosed in diagonally braced frames. Floor landings may be part of the stair system or the main structural floor. Freestanding stairs have unsupported intermediate landings and are usually constructed with fixed supports at the floors.

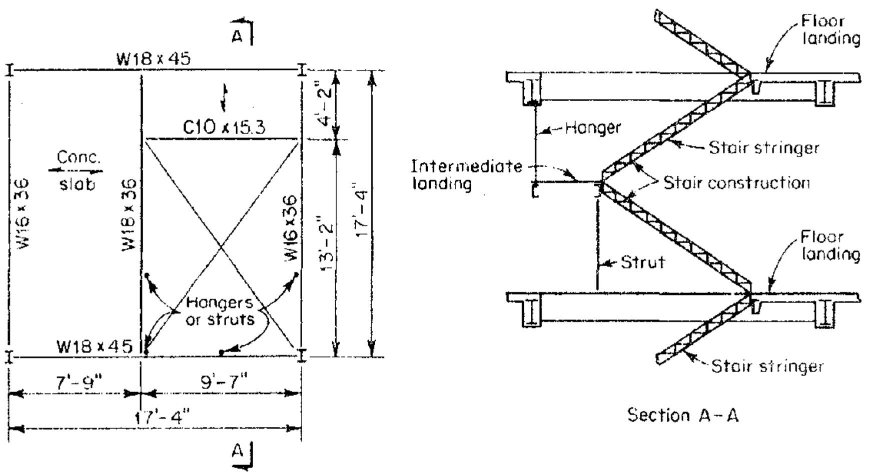
The spatial geometry of a staircase can be straight, circular (with a single center of curvature), curved (with two or more centers of curvature), or spiral (with a vertical center post). Variations are created by change of direction at intermediate landings. These include parallel flights ("dogleg," 180° turn at the landing), angled flights (turn other than 180°, frequently



(a) Concrete stair framing



(b) Concrete framing at stairwell



(c) Steel framing at stairwell

Fig. 1.2 Standard structural framing for stairways. (From Structural Engineering Handbook, Second Edition by Edwin H. Gaylord & Charles N. Gaylord, Editors. Copyright 1979, McGraw-Hill Book Company. Used with the permission of McGraw-Hill Book Company.)

90^o), and scissors stairs (parallel straight stairs running in opposite directions, usually separated from each other by a wall).

Stair construction is usually related to the primary structure of the building. In steel frame structures, metal stairs with metal or concrete treads are typical. Concrete and masonry structures may contain metal stairs, precast concrete stair flights, or cast-in-place concrete stairs. Construction varies with the intended use; a dramatic monumental staircase differs from a service stair in materials and details.

Metal stairs, of steel or aluminum, are typically prefabricated in sections and installed at the site. Flights may be supported by one or more stringers made of channel or I sections, steel plate with carrier angles, or steel sections and/or plates welded into rectangular boxes. Treads may be steel pans or subtreads, with or without risers, filled with concrete, terrazzo, tile, or other material with nonslip finish. Steel or aluminum treads and risers may be formed from checkered plate or gratings. Precast concrete steps may be supported by steel stringers. Landing platforms are similar. These platforms may be attached to the building structure by hanger supports with steel rods or bars bent over and welded or bolted to the top flange of steel floor beams. They may be carried on angle struts in walls, or by stringers or headers on bearing plates in loadbearing walls.

Metal stair flights and platforms may be factory fabricated, delivered to the site, and bolted and/or welded in place. Railings may also be attached to the flights and enclosure walls at the site. Stair soffits may be the exposed understructure or be plastered or covered with metal sheets. In many instances, details of fabrication and installation are left to the supplier, although the design professional may specify particular requirements.

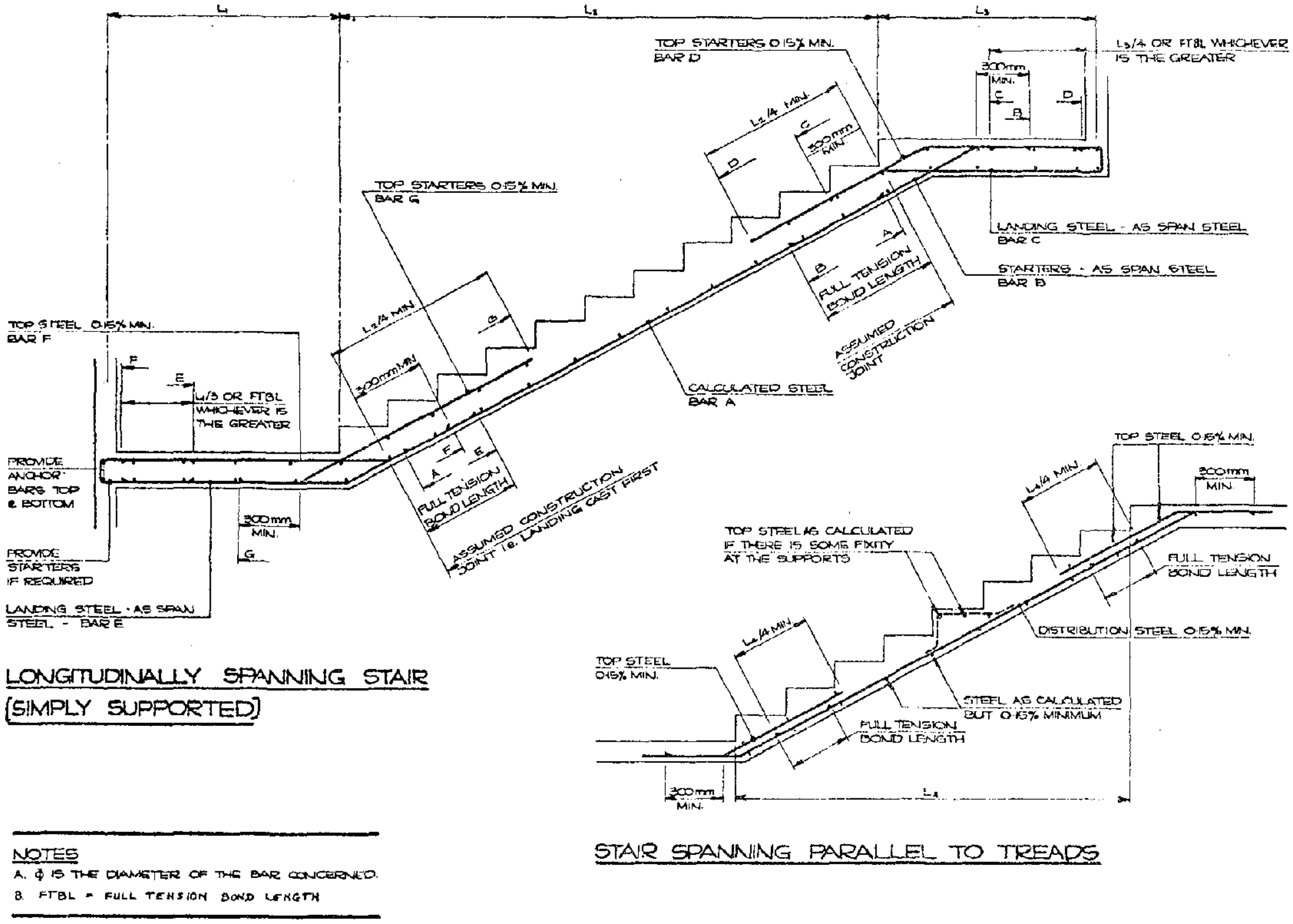


Fig. 1.3 Concrete stairway detail.
(Diagram from Earthquake Resistant Design, by David J. Dowrick, John Wiley & Sons, Ltd., 1977. Used with permission of John Wiley & Sons, Ltd.)

Reinforced concrete stairs may be cast-in-place monolithically with the surrounding structure, or formed or installed after the floors and adjacent walls are in place. Stair flights formed after the structure may be dowelled to the side walls or supported by beams or ledges at the landings. The landing connections may be ductile, or concrete slip joints with bolts, washers and slotted holes. These construction joints are also important with precast concrete flights, which may have embedded bars or angles for reinforcement and connection. Precast steps may be supported on slabs or subframes. The concrete slab may be cast in place first and the steps formed later. Concrete steps may be faced with some other material or left exposed. In the latter instance, some protection of the tread nosing may be needed.

Concrete stairs are typically designed for gravity loads as one continuous folded inclined slab or a monolithic slab-and-beam system simply supported at the landings. The slab may be a single flight or may include either or both landings. Gaylord & Gaylord (1979) illustrate some typical steel reinforcement schemes for smooth soffit stairs (see Fig. 1.2a). A more detailed reinforcement scheme for seismic design is indicated by Dowrick (1977) (see Fig. 1.3). Reinforcement details for sawtooth or slabless stairs are suggested by the Council on Tall Buildings, Group CB (1978). Chapter 5 of this report discusses current techniques for structural analysis of stairways.

2. PAST PERFORMANCE OF STAIRWAYS IN EARTHQUAKES

Many stairways in multi-story buildings have undergone strong seismic shaking satisfactorily, while numerous other stairways have suffered from minor to extreme damage. The former were used in evacuation as intended. The more severely damaged stairways impeded human movement, slowed rescue operations, interfered with transport of injured persons, and created hazards to the removal of possessions from condemned buildings. Although the relationship of stairways to structural systems has often played a very important role, study of this relationship has been neglected. The result has been poor seismic performance.

Damage has occurred to structures due to the behavior of stairways and to stairways due to the seismic response of the structural systems. Structures have been affected by (a) the creation of "short columns" due to landings connected at midheight, resulting in brittle shear failure (Figs. 2.1, 2.3), (b) the creation of "short beams," leading to a significant increase of shear (Fig. 5.1), (c) the creation of high local shear stresses in floor diaphragms due to the restraint offered by stairs and enclosure walls (Fig. 2.2), and (d) the introduction of torsional eccentricities (Figs. 2.4, 4.1, 5.2). Damage to stairways has included (a) the failure of brittle enclosure materials (Figs. 2.6, 2.10, 2.11), (b) cracking and spalling of concrete at the stair flight-landing junction (Figs. 2.7, 2.8, 4.2), (c) jamming of exit doors (Figs. 2.9, 4.4), (d) dislocation of nonstructural components such as light fixtures or seismic joint coverplates (Fig. 4.5), and (e) disruption of building services (Fig. 2.12). These conditions seriously affect the use of stairways for emergency egress and could become extremely dangerous should panic or fire ensue.

Actual information on stairway performance is sparse because (a) there have been relatively few major earthquakes affecting modern engineered buildings, (b) the reconnaissance and investigating teams usually arrive after the buildings have been evacuated, (c) past reconnaissance reports have focused more on the primary structure than on secondary and nonstructural components, (d) accounts of occupants' experiences in emergency exiting are infrequently published, and (e) stairway structural systems are rarely described in relation to the primary structural system.

This chapter presents a compilation of observations on stairway performance, taken from reports and articles on significant earthquakes of this century.

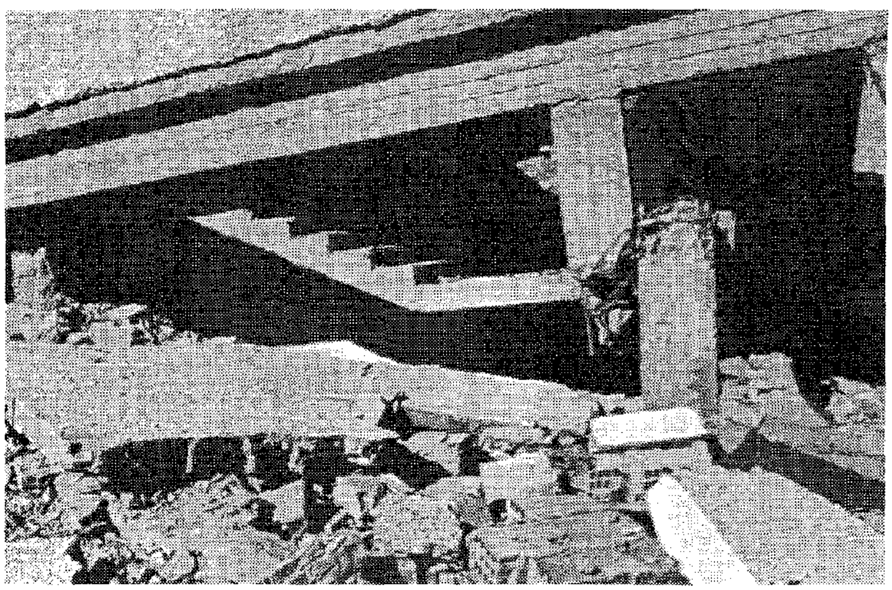


Fig. 2.1 Concrete column failure at stairway, Medical Clinic Building, 1980 El Asnam Earthquake. (Photo courtesy of V. V. Bertero and H. C. Shah.)

2.1 Seismic Influence of Stairways

Stairways are often heavy, permanent, rigid elements extending the full height of buildings, connected directly or indirectly to the primary structural system. During earthquakes the stairways may interact with the primary structure and unanticipated responses may occur.

> The response of a building to earthquake motion is affected by the stiffness and mass distribution of the load-carrying structure together with the stiffnesses and masses of the nonstructural exterior and interior walls including stairwells and elevator shafts. Often the stiffnesses of nonstructural elements are not considered by the structural engineer when determining the building seismic response. (Sharpe, 1972)

> External lift and stairwells...tend to act on their own in earthquakes, with force concentrations, torsions and out of balance forces which are difficult to predict without complex and expensive dynamic analyses. (Dowrick, 1977)

> The staircase cast monolithically with the frame behaved like a truss, and because of its rigidity, it attracted large lateral forces. After the connections between the inclined and horizontal platforms had been destroyed, the frame was called upon to take over the resistance of lateral forces. In most cases, this distress was observed only in the lower several stories. (Fintel, 1967)

> Architectural elements often participate in the initial stages of response until they crack, fail, or separate from the structural system. These nonstructural, but nonetheless important and costly elements and materials need more attention. In the first place, partitions, fireproofing, stairways, etc., can considerably reduce the initial natural periods of the building from those of the frame alone with, of course, all mass considered. Thus, the structural response begins with these shorter periods and, if nonstructural failure, slippage, or separation occurs, periods lengthen, sometimes drastically. (Blume, 1979)

Not only will periods change, but the modes of response may be expected to change as well. Thus, stairways are important building elements whose interactions with the primary structural system and other building elements require better understanding.

Fig. 2.2 Floor cracking at stair core, Banco Central, 1972 Managua Earthquake. (See also Fig. 2.10) (Photo courtesy of Loring A. Wyllie, Jr.)

2.2 Stairway Damage

Earthquake-induced damage has affected primary structures, stairway structures, stairway functions and appearance, life safety, and building economics. The following observations, comments and photographs were made in the days and weeks after major earthquakes. Most were recorded by structural engineers and architects experienced in seismic damage analysis. Damage has been classified by type of component affected, as a means for emphasis and comparison. This indicates the variety and range of damage possibilities, although not necessarily the mechanisms which produced the damage.

Fig. 2.3 Steel column failure at stair landing, Cordova Building, 1964 Alaska Earthquake. (See also Fig. 2.9) (Photo courtesy of the American Iron and Steel Institute.)

2.2.1 Damage to Primary Structures

As "nonstructural" elements, stairway and stair enclosure contributions to the stiffness of the building structure have not always been considered. Local failures of primary structural elements have occurred adjacent to stairways due to the resistance provided by stair flights, landings, and enclosure walls.

Anchorage, Alaska, 1964

> The southeast corner column [of the Cordova Building] (Fig. 2.3) was substantially stiffer than the rest of the columns in that story because of the stair landing, hence, the lateral displacement of the building induced more severe local deformation in this column than in the other two columns in the same bent. (Berg & Stratta, 1964)
>
> The analysis of the Cordova Building indicates that there would have been little damage if there had been no concrete elevator [and stair] shaft in the building and no concrete wall sections and if the stairway had not improperly restrained the corner column. (Benuska & Clough, 1973)

San Fernando, California, 1971

The structural repair was required at the intermediate stair landing between the first and second floors [of the Holiday Inn on Marengo Street]. Cracking and spalling occurred at the slab and beam column joints (Fig. 6.1). (Blume, 1973c)

Managua, Nicaragua, 1972

The potentially most serious structural damage to the tower [of Banco Central] was the cracking of the floor slab near the elevator cores...and at the stairs (Fig. 2.2). (Meehan, Degenkolb, Moran & Steinbrugge, 1973)

Veracruz, Mexico, 1973

[The Packard Apartment Building complex in Orizaba] consisted of three, three-story buildings linked by terraces and stairways. Two of the buildings collapsed killing ten people, injuring 40 and crushing 20 cars parked underneath on the ground floor....The whole complex was torsionally unbalanced because of the linking terraces and stairways which provided shear transfer between adjacent buildings. (Irvine, 1973)

Guatemala City, Guatemala, 1976

[At Javier High School,] the light ornamental enclosure around the staircase frame provided sufficient rigidity and strength to tear the column from the roof slab. (Sozen & Roësset, 1976)

Friuli, Italy, 1976

Twisting of the [3-story dwelling house in Artegna] around the staircase stiffened with masonry walls (Fig. 5.2). (Glausner, 1977)

Miyagi-Ken-Oki, Japan, 1978

[Obisan Building in Sendai] (Fig. 4.1) is a 3-story reinforced concrete frame building with a soft first story, one span in each direction. The columns were inadequate to resist the torsional force caused by a heavy eccentric stairwell that cantilevered over the column line at the right end of the building. (Yanev, 1978)

El Asnam, Algeria, 1980

The block [of Galerie Algerienne] that remained standing besides the moment resisting space frame, had a well infilled R/C frame shaft for the stair. Despite the fact that this shaft introduced considerable torsional forces, its stiffness and strength was sufficient to avoid the collapse of this block. (Bertero & Shah, 1982)

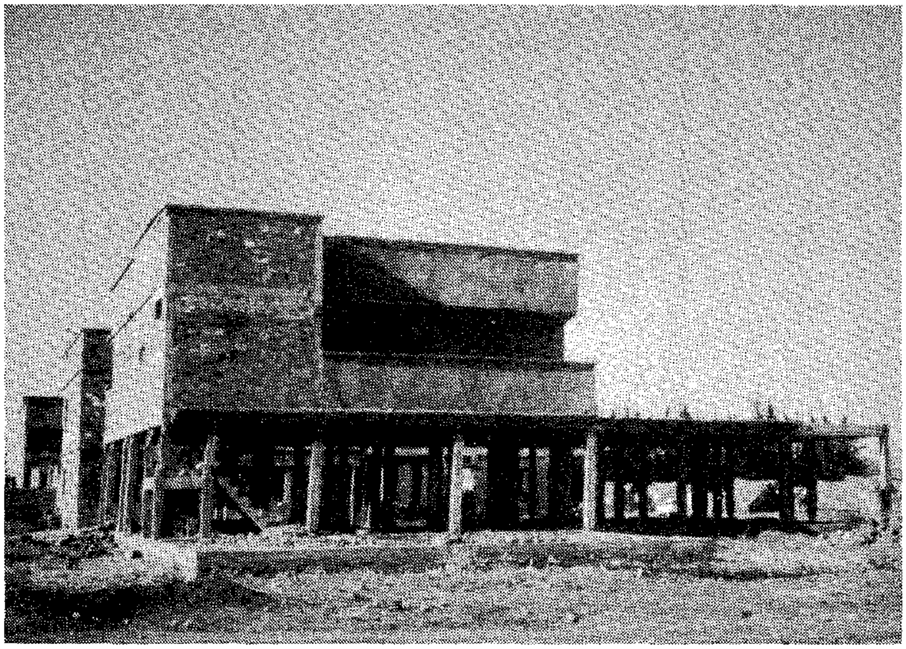


Fig. 2.4 Torsional effects of stairway, three-story house at El-Attaf, 1980 El Asnam Earthquake. (Photo courtesy of V. V. Bertero and H. C. Shah)

> The majority of stairways are constructed of reinforced concrete and are attached to the columns at midheight of each story, thus originating short columns, which failed. Furthermore, because of their locations and stiffening effects, these stairways originate significant torsional moments in the whole building during earthquake ground motions (Fig. 2.4). (Bertero & Shah, 1982)

The stiffness contribution of stairways may induce local primary structural failures and modify the overall structural response. Affected structural elements include columns, girders, floor diaphragms, and shear walls. The stiffness and especially the eccentricity of stairways may significantly influence the response of a structure, which in extreme cases has resulted in primary structural failures and even collapse. These important interactions can not be left to chance.

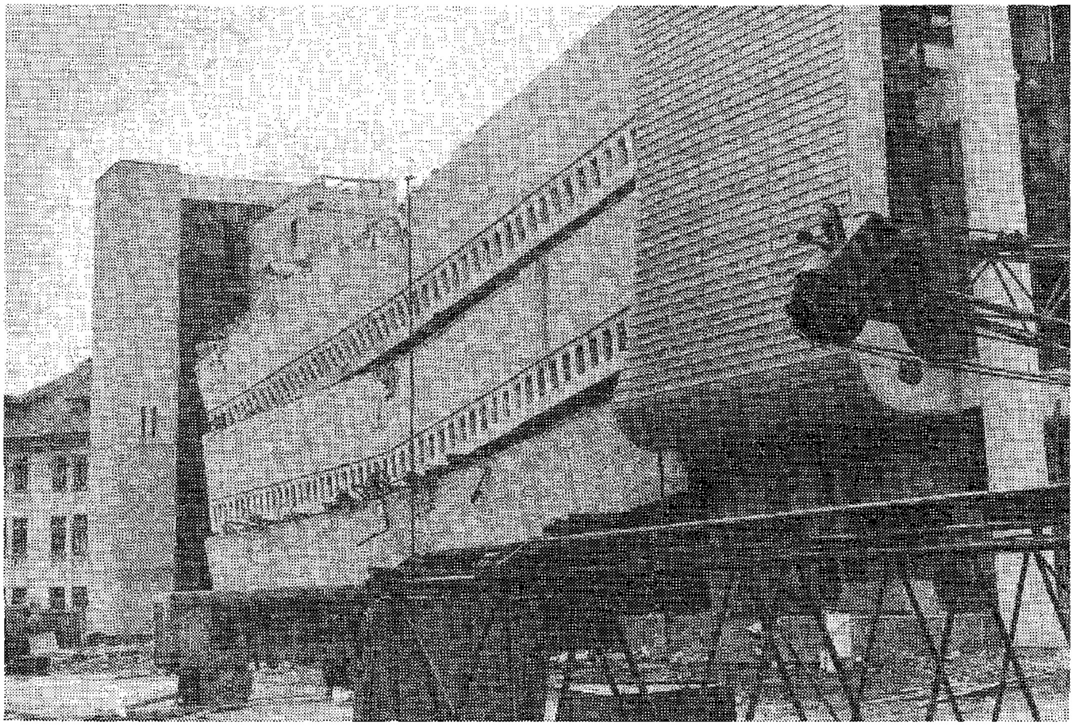


Fig. 2.5 Stair towers standing adjacent to collapsed main building, Computing Center, Bucharest, 1977 Romania Earthquake. (Photo courtesy of Glen V. Berg.)

2.2.2 Damage to Stair Towers

Stairways may be contained in structurally independent towers which are separated from the main structure by small gaps and coverplates. During earthquakes, out-of-phase relative responses of stair towers and primary structures can cause pounding and damage to the separation joints. The tall slender shape of stair towers increases their tendencies toward overturning and foundation damage. Structural failure of a stair tower can seriously impair evacuation of the building.

Santa Rosa, California, 1969

> [At the west stair tower of the Social Service Building,] movements did occur at the structural separation, and some pounding damage also apparently occurred. In addition, it is quite possible that a substantial seismic force was transmitted from the main building to this stair tower through friction at the structural separation. (Steinbrugge, 1970)

San Fernando, California, 1971

> [Olive View Hospital] building had four stairtowers, three of which collapsed (Fig. 1.1). Had the earthquake struck later in the day, the stairtowers' recreation rooms would have been occupied. The detailed survey of damage in the field revealed that Towers A, B, and D collapsed due to failure in their first floor structural system and ground story columns. These towers overturned backwards, falling away from the upper stories of the main building into the ground story....Tower C was the only tower to remain standing after the earthquake; however, it was tilted in about 5^{0}. The damage pattern indicated that this tilt was caused by the northward movement of the main building rather than by the response of the tower itself. (Bertero & Collins, 1973)

Managua, Nicaragua, 1972

> In the center of each building [of Simon Bolivar Elementary School] was a stair tower. Local impact between this stair tower and the classroom building was evident. Cracking of the plaster in the stair tower and dislocation of the plywood panels from the roof soffit was visible. This occurred because of lack of adequate separation between the stair tower and the classroom building. (Amrhein, Hegemier & Krishnamoorthy, 1973)

> The stair unit [at Banco de Vivienda], structurally separated, remains plumb but the building tilted 6 inches to the west, away from the stair tower. (Meehan, Degenkolb, Moran & Steinbrugge, 1973)

In another instance where the main building suffered great damage, the stair towers provided refuge for building occupants fleeing the collapsing main structure.

Bucharest, Romania, 1977

> [The Computing Center] was a flat plate building with service towers at either end housing the stairwells, elevators, etc., and a main building in between. The central building was structurally separated from the service towers. The service towers remained intact, but the central building collapsed....(Fig. 2.5). (Berg, 1980)

El Asnam, Algeria, 1980

> It is important to note that alongside the [one unit of Maison de La Culture] that remained standing was a stair shaft of reinforced concrete. Although this stairway was structurally independent of the unit, it appeared to have been so closely constructed that it supported or constrained the deformation of the adjacent building unit. Inspection of the building that remained standing showed that this unit was at the edge of collapse. [A similar unit without stair shaft did collapse.] (Bertero & Shah, 1982)

These examples underscore the need for careful structural analysis and design of separated stair towers, so that unanticipated responses can be avoided. Attention must be paid to separation distance, types and materials of separation joints, and overturning stability of the tower. Properly designed stair towers can become important refuges during earthquakes or fires; overturned towers are extremely hazardous.

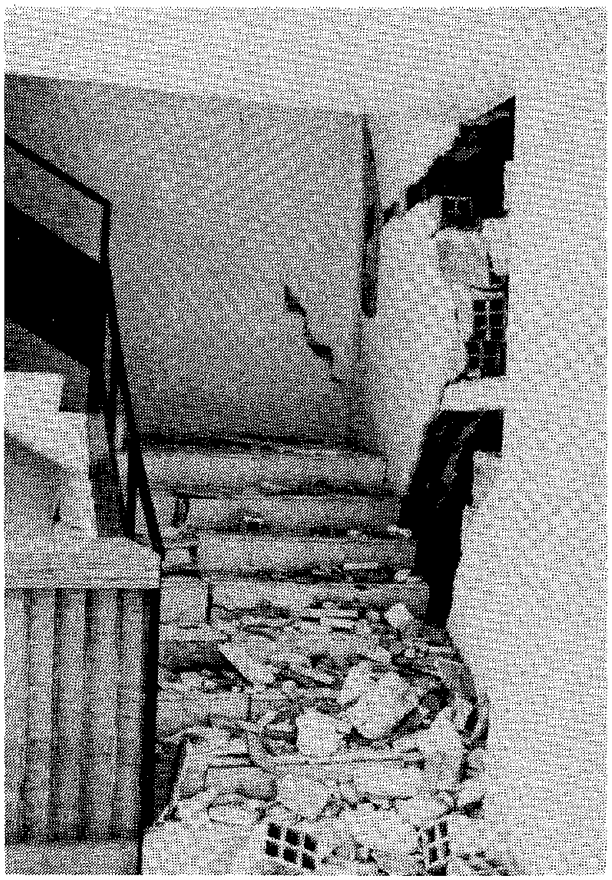


Fig. 2.6 Shattered tile enclosure wall, American School, 1972 Managua Earthquake. (Photo courtesy of Henry J. Degenkolb.)

2.2.3 Damage to Stair Enclosures

Stairways are frequently enclosed by structural or nonstructural walls for fire protection, security, and/or lateral force resistance. In older buildings these enclosures may be constructed of unreinforced masonry (especially clay tile block, brick, or concrete block); earthquake-induced brittle failures are very typical of such construction. Modern enclosure materials, such as reinforced concrete, metal lath and plaster, and metal stud and gypsum board, have performed much better. Yet even these materials have exhibited considerable cracking, particularly at joints or diagonally. Wall repair and repainting has been a significant nonstructural expense following earthquake.

San Francisco, California, 1906

> Débris consisting principally of plaster and hollow tile blocks frequently covered all the floors to a depth of from two to eight inches, and in many cases the impact of the blocks and the abnormal loads wrecked the stairways. (Himmelwright, 1906)

Long Beach, California, 1933

> Damage to partitions or enclosure walls around stairways and elevator shafts of steel frame buildings was very noticeable; stair construction introduces diagonal bracing between floors and causes this portion of the structure to take more than its share of the horizontal thrust. (National Board of Fire Underwriters, 1933)

Anchorage, Alaska, 1964

> ...fireproofing concrete in the bottom of a stair landing in the West Anchorage High School broke loose and littered the exit. In the same school a structural failure caused the finish tile on the wall of a stairway to break loose (Fig. 5.5). This type of damage suggests that brittle finish materials should not be used in exits, unless all mounting details are of earthquake-resistant design. (Ayres, Sun & Brown, 1973)

> The failure of unreinforced-concrete-masonry-unit exit walls were in sharp contrast to the excellent performance of the lath-and-plaster stair shafts in the Cordova Building and in Providence Hospital, where the plaster was extensively cracked, but the exits were usable. This was also true in the plastered corridors of the Mt. McKinley apartment building. (Ayres, Sun & Brown, 1973)

San Fernando, California, 1971

> The westerly stair well [at Holy Cross Hospital] was badly cracked up and full of debris. The only useful exit available was the northeast stair well, though walls here were badly cracked also. (Spracklen, 1973)

> Plaster walls in the stairwells and elevator shaft [of the Union Bank Building, Sherman Oaks] cracked and portions fell. Most of the damage occurred from the first through the fourth floors. (Blume, 1973d)

Managua, Nicaragua, 1972

> In the Banco Central (Fig. 2.10) the stairs remained structurally sound; however, the walls of the stairwell enclosure were clay tile and the displacement of the moment-resisting frame was sufficient to shatter the tile infill walls, leaving the stairs littered with debris to such an extent that their use for evacuating the building under panic conditions in the dark would doubtless have led to many injuries and possibly even loss of life. It was fortunate that the building was unoccupied at the midnight hour when the event occurred. Brittle walls are to be avoided in stairwell enclosures. (Berg & Degenkolb, 1973)

> Above the stairways [of the Judicial Building] the wall was hollow clay tile with a polished stone face, most of which fell. (McLean, 1973)

Guatemala City, Guatemala, 1976

> The debris of the locally shattered brick masonry walls littered the stairwells on both east and west sides of the [National Theater, under construction]. No other distress from the earthquake was apparent in the theater. (Smith, 1976)

El Asnam, Algeria, 1980

> Large portions of collapsed partitions blocked the stairways of several buildings, making evacuation of these buildings difficult. (Bertero & Shah, 1982)

Brittle stair enclosure construction and finish materials have proved particularly hazardous due to falling debris. Adequate reinforcement of concrete and masonry walls and anchorage of brittle finish materials may reduce this type of damage. Brittle stair enclosures of doubtful seismic resistant construction may be found in many older existing buildings; retrofitting or rehabilitating these enclosures needs serious immediate consideration. In all cases, the sensitivity of enclosure walls to relative displacements of the structure must be evaluated. Stair enclosure systems in very flexible moment-resisting frame structures can be expected to perform differently from those in very rigid shear wall or braced frame structures.

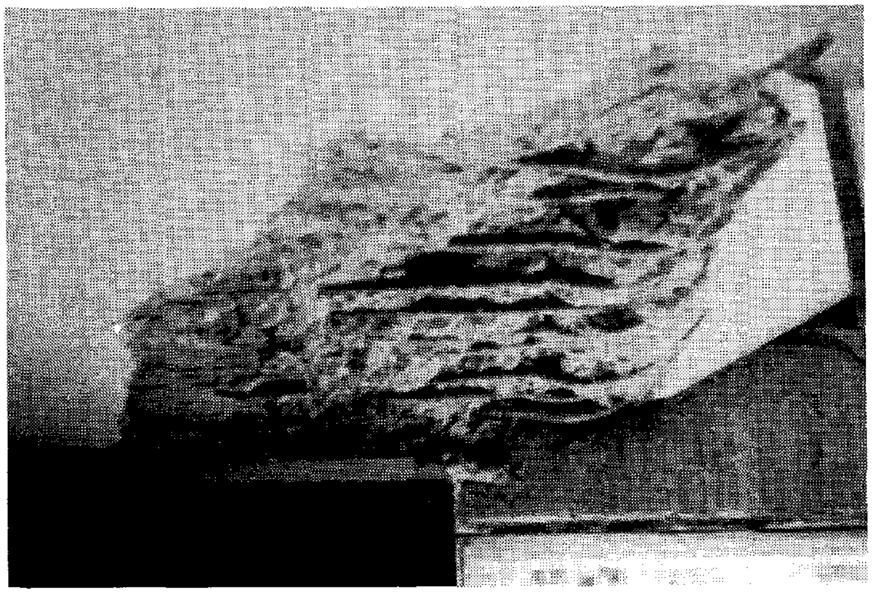


Fig. 2.7 Stair landing damage, Residencias Union Building, 1967 Caracas Earthquake. (Photo courtesy of the Portland Cement Association.)

2.2.4 Damage to Stairs

Assemblies of stair treads, risers, and landings have often been vulnerable to seismic actions. Considerable damage may be induced by stresses in the inclined flights or at the connections to surrounding frames or walls. A recurrent problem has been the impact of falling debris from adjacent enclosure walls, which may damage treads as well as litter the pathway.

San Francisco, California, 1906

> Marble and slate treads in stairways should be supported by metal underneath. In many cases where the treads of the stairways were simply outline framing supporting marble and slate slabs, the latter were destroyed or broken by the fire, and the stairways rendered unserviceable and dangerous. (Himmelwright, 1906)

Skopje, Yugoslavia, 1963

> Almost every staircase the writer saw in Skopje was damaged, especially at the first story. Although evidently not considered in the design calculations, the staircases developed considerably large lateral forces as a result of the structural deformations resulting from the earthquake. While they were rigid enough to develop these forces, their reinforcement was very light. (Sozen, 1964)

Anchorage, Alaska, 1964

In a stairwell in Elmendorf Hospital, the effect of flexibility was achieved in a reinforced concrete stairway by inserting a horizontal construction joint between each landing and the bottom riser of the flight of stairs above it. This permitted movement between the stairs and landing, and although the stairwell walls showed minor cracking, the stairs were undamaged. (Berg & Stratta, 1964)

The stair [in the Hoblit Building] pulled slightly away from the wall since there was no tie between these units. (Steinbrugge, Manning & Degenkolb, 1967)

Caracas, Venezuela, 1967

In a number of structures, distress at the junction between the inclined and horizontal stair platforms [landings] was observed. (Fintel, 1967)

In the stairway-to-landing junction [in the Residencias Union] (Fig. 2.7), concrete had spalled and the 7/8-in. bars, which were 7 in. on center, showed signs of yielding. This distress was experienced in the lower stories only. (Fintel, 1967)

The stairway, acting as an unintended bracing element, proved to be one of the most rigid elements in the first story of [the San Bosco] building (Fig. 4.2) and consequently suffered major damage. The decrease in structural damage at the higher stories observed many times in this earthquake is graphically illustrated by the damage to this stairway. (Hanson & Degenkolb, 1969)

Tokachi-Oki, Japan, 1968

In the stair slabs shear failure was often found near the connecting portion between the landing slab and the stepped slab. Particularly, in buildings whose quantities of walls were small or in the staircase in which stepped slabs were simply supported without side walls, those shear failures were liable to be found. In those cases, the stair slabs acted as the truss members in the building and they have acted as structural elements resisting seismic forces. Therefore a concentration of shear forces was expected in the stair slabs. (Suzuki et al., 1971)

Interior stairs to the gallery [of the gymnasium of Shichihyaku Primary School] moved about one meter (Fig. 5.7). (Suzuki et al., 1971)

The staircase and its surrounding walls in the middle part of the north-west wing [of Hakodate College] were entirely collapsed in the first story. The outdoor emergency staircase of steel, which had been anchored to the north-west end wall, was shaken off and overturned. (Suzuki et al., 1971)

Mexico City, Mexico, 1968

[In La Fragua #3 Building] there were straight steel stringers framing into steel floor beams. These could act as struts and did, being bowed out of line and permanently deflecting the supporting beams. (Driskell, 1968)

San Fernando, California, 1971

Some damage was also noted in the stairwell [at Indian Hills Medical Center] where the connections of metal stairs pulled away from the concrete wall at the landings. Although usable, the stairs were "shaky." Elevators were inoperative immediately after the earthquake. (Lew, Leyendecker & Dikkers, 1971)

Steel stairs at the first, second, and third floors [of the Union Bank Building in Sherman Oaks] pulled away from the supporting landings and the connections required rewelding. (Blume, 1973d)

[At Los Angeles High School there were] bent steel treads of exit stairs caused by falling debris. (Jephcott & Hudson, 1974)

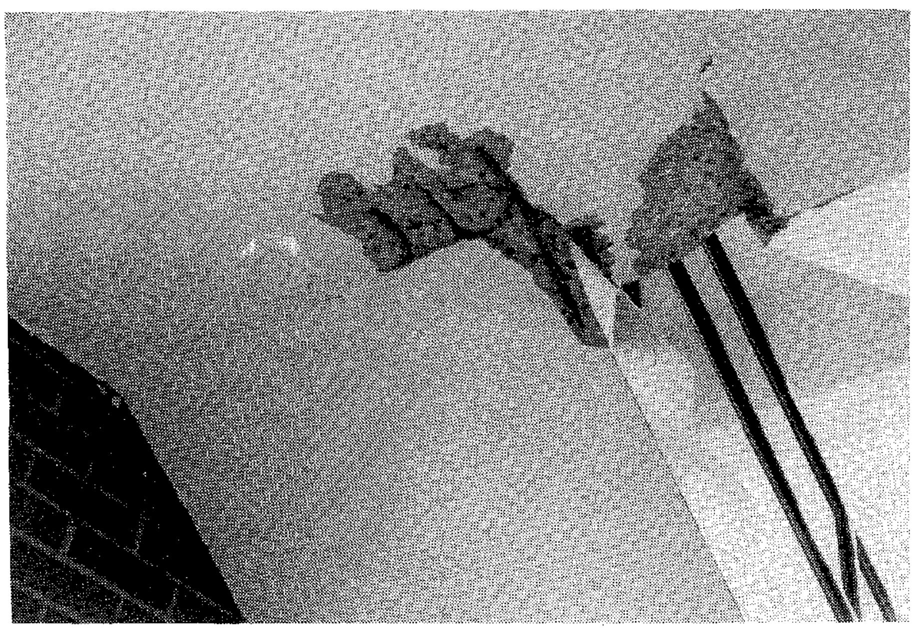


Fig. 2.8 Stair landing damage, Pacoima Lutheran Hospital, 1971 San Fernando Earthquake (see Fig. 5.6). (Photo courtesy of Paul C. Jennings.)

Managua, Nicaragua, 1972

The stairways at the elevators [of the Social Security Building] were severely damaged and shoring had to be installed at several levels...Longitudinal reinforcing appears to have been bent to conform to the shape of the bottom of the stair slab at the landing and a section on the drawings showed such a condition without provision for resisting stress components that would

> tear the reinforcing out of the slab. The stair slab was fractured entirely through the slab at the top step tearing out the reinforcing. (McLean, 1973)

Lima, Peru, 1974

> The walls of the Student Union [at the National Agrarian University] were separated from the columns, but the stairways and elevator shafts were rigidly connected to the floor slabs, thus creating stress concentrations on these elements. The staircase was severely damaged. (Husid, 1977)

Stairs pose potential life safety hazards and require careful attention in design and analysis. The designer must not only consider the integrity of the stairway substructure, its support, its stability, and its ability to resist imposed loads (including the impact of debris), but must also investigate the possibility of interaction with the primary structure. Due to the typical diagonal brace-like configuration of stairs, they may unintentionally increase the lateral stiffness of the structure and consequently reduce the fundamental period and mode shape significantly. This change in dynamic characteristics often results in attracting higher seismic forces than analysis of the pure structure would indicate.

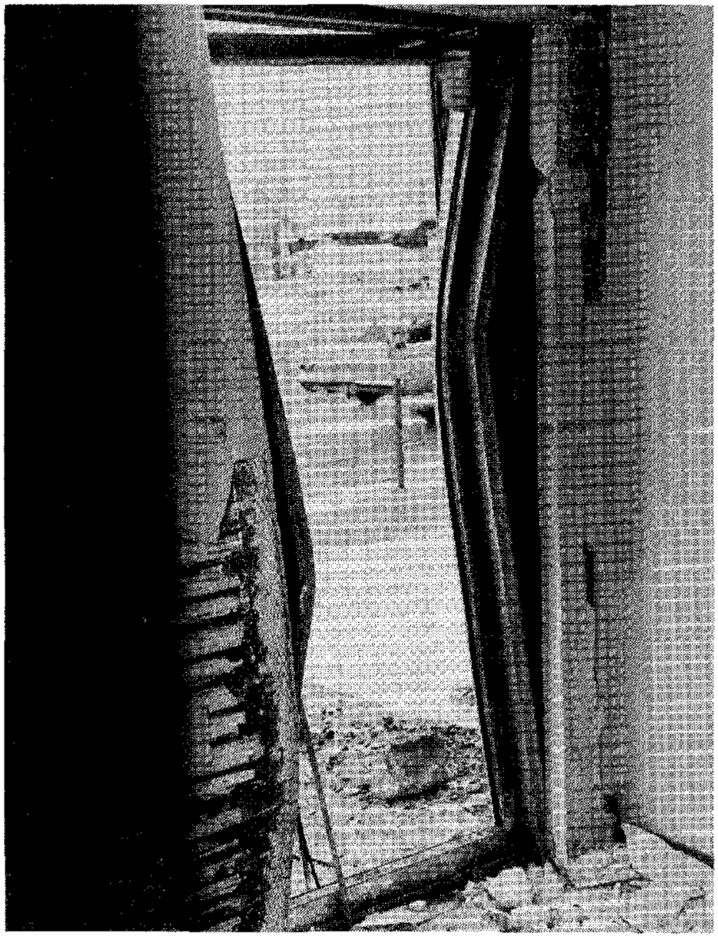


Fig. 2.9 Doorway at the bottom of the stairs, Cordova Building, 1964 Alaska Earthquake (see also Fig. 2.3). (Photo by the Bureau of Land Management, from the files of the Earthquake Engineering Research Library, California Institute of Technology.)

2.2.5 Damage to Other Stairway Components

Seismically-induced movements of stairs and, in particular, stair enclosures affect the condition of doors, windows, and attached elements. Movements of the entire building affect the performance of electrical and mechanical systems, which have interfered with emergency lighting, ventilation, communications, and elevators. Such failures may prove dangerous in their own right and increase the hazards from fire or flooding.

Anchorage, Alaska, 1964

> Exit doors were jammed during the earthquake by structural failures around the doors, as in the Anchorage-Westward Hotel, or by deformed frames, as in the West Anchorage High School auditorium. (Ayres, Sun & Brown, 1973)

Tokachi-Oki, Japan, 1968

Large fixed glasses [windows] in staircases were easily broken and this is very dangerous. There was one such case where the staircase could not be used due to glasses broken during the earthquake. (Suzuki, _et al_., 1971)

San Fernando, California, 1971

The glass in the enclosure surrounding the exit stairwell of the gymnasium [at Crescenta Valley High School] shattered and fell into the stairwell and could have been a serious hazard. (Lew, Leyendecker & Dikkers, 1971)

The doors to the interior stairwell on the second and third floors [of Kaiser Foundation Hospital] were rendered inoperable due to the crushing of the spandrel beam in the shear wall (Fig. 4.4). (Lew, Leyendecker & Dikkers, 1971)

The flooded stair at the two-story Lockheed Building 147... was caused by the broken cast iron fitting in the fire-sprinkler line.... (Ayres & Sun, 1973)

A major portion of the owner-incurred repair cost (60%) [for a 19-story ductile steel building] resulted from stairwell repainting. (Hart & Stillman, 1972)

Managua, Nicaragua, 1972

One of the subtle phenomena observed in the Banco Central Building was the jamming of emergency exits. A building with a flexible structural system is not likely to return to its original geometry after a damaging earthquake and it takes little distortion to jam a stiff door. Had the earthquake been followed by a fire, the jamming of these exits during working hours, with the elevator system inoperative, would have been catastrophic. (Sozen & Matthiesen, 1975)

In the 13th floor stair corridor [of Banco Central] a fire extinguisher anchored to the exterior wall pulled loose from its fastenings and came to rest 17 feet away. (Meehan _et al_., 1973)

Failure of electric supply, without emergency back-up, results in unlighted staircases, which are the only means of escape from a building when the elevators fail. These then become extremely hazardous for people trying to use them, especially when debris from broken walls and ceilings has littered the treads and landings. The conditions after the earthquake in the staircases of the Banco Central de Nicaragua, for example, would have caused large loss of life and injury to many persons had the earthquake happened at the hour when the building was populated. They were passable only with difficulty. (Ferver, 1973)

Guatemala City, Guatemala, 1976

> [At the INFOM Building,] the concrete stair railings were damaged at several floor levels. These were reportedly not designed as structural elements, although they acted as such. (Wosser, 1976)

Santa Barbara, California, 1978

> Minor damage to seismic joints was reported in most of the multistory buildings on campus. In one case this minor damage resulted in a safety hazard when a damaged seismic joint prevented the opening of a second floor emergency exit on the north side of the UCSB Library. (Fig. 4.5) (Miller & Felszeghy, 1978)

The seismic performance of all components of emergency exit routes must be evaluated so that the corridors and stairways serve their intended purposes. Intact stairs cannot be used if the doors to them are jammed shut or if broken glass makes them too dangerous. Attachments and bracings for the variety of fixtures and equipment found in stairways must be designed for expected seismic forces to reduce potential safety hazards and economic losses.

Fig. 2.10 Stairway hazards from debris and broken handrails, Banco Central, 1972 Managua Earthquake. (See also Fig. 2.2) (Photo courtesy of Henry J. Degenkolb.)

2.3 Interference with Evacuation

The most critical life safety issues of stairway performance in earthquakes are the interference of stairway structural behavior with a building's overall seismic response which results in collapse, and the interference of damage with emergency exiting and rescue. People tend to flee buildings during earthquakes; the Modified Mercalli Intensity Scale characterizes an intensity VII earthquake: "Everyone runs outdoors." However, that reaction may prove dangerous.

> DO NOT RUSH OUTSIDE. Stairways may be broken and exits jammed with people....If you must leave a building, choose your exit as carefully as possible. (Standard earthquake safety advice, author unknown.)

Hazards may be compounded if people attempt evacuation before building motions have subsided and run into the path of falling debris, as occurred in the long duration Alaska Earthquake of 1964. People leave buildings to escape real or perceived dangers and to check on the safety of family, home and business. These psychological factors relate importantly to the use of emergency exits.

> There may well be a strong feeling that the building may collapse, start burning, or that means of escape may be cut off. The individual may attempt immediate escape, unaware of attendant risks of elevator malfunction or of falls while rushing down stairs....Finally, the escape route will almost certainly be shared by others who may not necessarily be travelling at the same speed or even in the same direction (people may be re-entering the building for a variety of reasons). (Pauls, 1977)

> In the 1971 San Fernando earthquake, plaster ceilings and walls in primary exit stair towers were damaged due to drift in several high-rise structures. The falling of small portions of plaster is somewhat hazardous to occupants during evacuation, but the more serious consequence can be panic in the minds of the laymen, who would assume structural failure was occurring. Stair towers are often the stiffest elements in a building and yet on many occasions experience great damage. Stair towers are absolutely vital for evacuation and for access of rescue teams. The tower must be designed to remain intact. (Hillman & Mann, 1973)

> We shouldn't be smug, however. We are also capable of designing buildings such as the seventeen story Triangle Building in Guatemala City which had a single three foot wide stair with winders, no lights, no handrails, and no ventilation. During the earthquake residents in the upper portion of the building remained in their apartments rather than trying to escape on this stair. Fortunately, there was no fire. (Hartray, 1978)

Much more must be learned about emergency exiting behavior, particularly in large and tall structures, to verify the adequacy of provisions for both fire and earthquake. A hypothetical 40-story office building, containing two 44" stairs and not considering elevator use, has been analyzed for evacuation time.

> Assuming that 4500 able-bodied occupants actually start to leave when notification is given, the total evacuation via [two] 44-in. (1120 mm) stairs would take almost 40 minutes....Note that this entails a wait of nearly 27 minutes, either on the office floor or in the exit stair before the last evacuee starts to descend. With all 4500 in the exits simultaneously, there would only be about 1.8 sq. ft. ($0.17m^2$) of stair area, or half of one tread, per evacuee. (Pauls, 1977)

This study does assume completely functional stairway systems, without jammed doors, debris on the treads, or darkness due to power failure. It also assumes rational human behavior.

> Think for a minute of the billions of dollars invested in the United States in tall buildings in areas designated seismic zone three. How do the occupants of those buildings respond when there is marked shaking of the earth? Do people immediately jam halls and stairwells? Or do the occupants simply stay in the area where they were when the shaking started? Does behavior change if the shaking continues for more than ten seconds? Since fire often follows earthquakes, are people in tall buildings generally aware that there is increased fire hazard in such a setting? (Haas, 1977)

Data collection following earthquakes should include interviews and questionnaires of building occupants, owners, and rescue workers to record particular hazards encountered and their effects on human movement. Attention must be given to evacuation of injured and disabled people, to disorientation caused by darkness or long descents, to obstructions in exit routes, and to component and equipment failures. The analysis and publication of this information could advance the practice of building design and guide further investigations.

Fig. 2.11 Fatal collapse of masonry walls into stairway, Enlisted Men's Service Club, 1964 Alaska Earthquake. (Reproduced from The Great Alaska Earthquake of 1964--Engineering with permission of the National Academy of Sciences, Washington, D.C.)

2.3.1 Stairway Damage and Evacuation

It is fortunate that most major earthquakes in the United States have occurred late at night, early in the morning, or at other times when large buildings were not fully occupied. This has significantly reduced casualties due to exit path damage, as many observers have noted. Nevertheless, stairway damage has impaired emergency egress, rescue operations, and removal of possessions from condemned buildings.

Anchorage, Alaska, 1964

> In the Enlisted Men's Service Club at Fort Richardson, a man was killed by falling concrete-masonry units at the foot of the exit stairway (Fig. 2.11). The entire stairway was covered with debris and escape was impossible. A portion of the concrete-masonry unit wall also collapsed in another exit stairway. (Ayres, Sun & Brown, 1973)

There were two men in the control tower of the Anchorage Airport. The controller who rode the building down came out alive. The man who ran down the stairs was killed. (Degenkolb, lecture, 1982)

Tokachi-Oki, Japan, 1968

Outdoor fire-escapes attached to the ends of the corridors [at Okamisawa Primary School] (Fig. 4.6), were pulled out during the earthquake for their wrong construction work. One of them completely fell down. Fortunately, no pupils or teachers were injured, because the pupils didn't try to escape their classroom obeying their teacher's direction during the severe earthquake motion. (Suzuki, et al.)

San Fernando, California, 1971

At Olive View Hospital, 600 patients had to be removed by using two interior stairways because the elevators were inoperative and the main stairwells at the end of each wing separated from the building (Fig. 1.1). Flashlights had to be used for lighting because the regular and emergency power systems failed. Some patients were trapped in their rooms and had to be freed. It took 30 minutes to evacuate the ambulatory patients, and others had to be carried out by a stretcher. (Olson, 1973)

Also, had a fire occurred [at Olive View Hospital], which is quite possible under the circumstances, a disaster could have ensued as only two small stairs were usable for evacuation and these had been damaged and distorted by the building deformation (Fig. 4.7). (Frazier, Wood & Housner, 1971)

About 170 patients were evacuated [from Holy Cross Hospital] by means of an exterior stairway at the east end of the seven-story tower. Rescue workers entered through an interior stairwell near the west end of the tower to avoid interference with the evacuees. During the evacuation emergency power and oxygen cylinders were in use. A strict no smoking or open flame policy was enforced as a safeguard against fire since there was no water available. (Lew, Leyendecker & Dikkers, 1971)

Managua, Nicaragua, 1972

[At Hotel Managua Intercontinental] the two stairways start at the second floor and continue upward to the eighth floor. The only stairway between the ground floor and the second floor is the outside stairway....In the dark with the elevators out of operation, the hotel guests had to descend in the central stairways to the second floor level, walk to the end of the hall and down the exterior stairway to the ground. Little imagination is needed to predict the disaster had a fire

> occurred at the west end of the second floor corridor. (Aktan & Hanson, 1973)

Guatemala City, Guatemala, 1976

> At the time of the principal shock, 3:00 a.m. February 4th, the children who live-in were sleeping in the dormitory areas of the Escuela De Niñeras [Nursery School] on the upper floors. A steel gate isolating these upper floors from the ground level became jambed at this time and as a result the children could not be immediately evacuated from the building.
>
> It is likely that most of the damage to the building resulted from this principal shock bringing the building nearly to collapse. The lesson is clear; the importance of a seemingly minor building component, the steel gate, can be seen to be potentially very great in terms of life safety while relatively insignificant in terms of cost and structural importance. (Axley & Bertero, 1979)

Safe evacuation via damaged stairs depends on the ability of building occupants to perceive hazards (such as debris, shattered glass, broken treads, detached stair flights) and to modify their actions accordingly. Lack of care in moving around after an earthquake can transform a serious inconvenience into a life safety hazard.

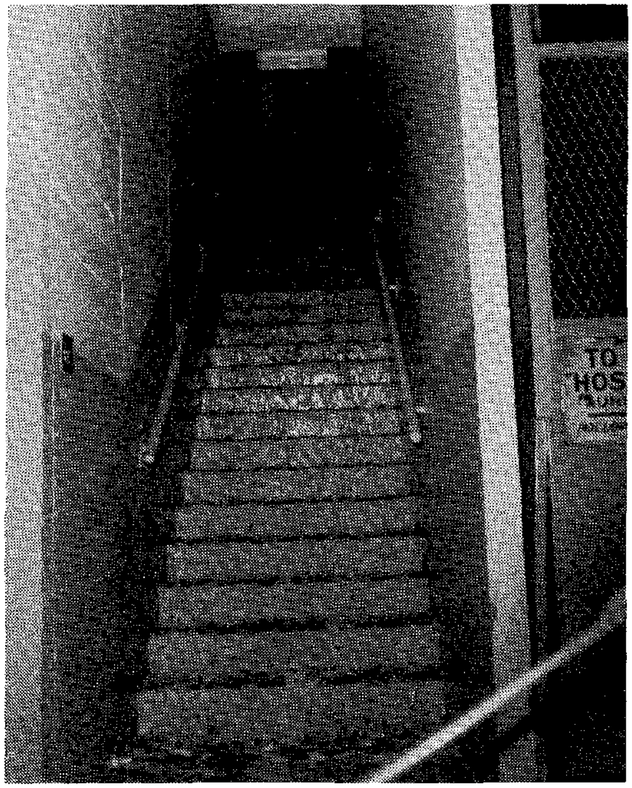


Fig. 2.12 Stairway flooded by broken sprinkler line, Lockheed Building 147, 1971 San Fernando Earthquake. (Photo courtesy of the Lockheed-California Company.)

2.4 Earthquakes and Fires

Intense, wide-spread conflagrations followed major earthquakes in San Francisco (1906) and Tokyo (1923). Although these holocausts have not been repeated in recent years, many building fires have resulted from earthquake damage. Possible causes included broken gas lines to appliances and equipment, spillage of flammable materials, electrical system malfunctions, accidental ignition, and arson. Since fire control is the primary concern of fire departments, rescue of people trapped in non-burning buildings could be delayed. Disruptions in emergency communications have impeded the response of fire departments to locating fires and assisting evacuations.

> It is not enough that tall buildings refrain from collapse in an earthquake. At a minimum they must make possible the very rapid evacuation of the building occupants. When elevators stop working and stairwells are covered here and there with fallen materials, the situation is ripe for a fire holocaust, especially if panic develops. (Haas, 1977)

> A compounding problem during earthquakes will be structural damage to fire walls or fire barriers....High-rise buildings require two-hour fire walls around vertical stairways. Structural damage to such walls may permit ready passage of fire and could cause a catastrophe in high-rise buildings. (Fulton, 1973)

> Stairways in most high-rise structures are designed to resist spread of fire for at least two hours and act as an area of refuge as well as a means of egress. If an earthquake is of sufficient intensity to destroy this integrity, these shafts, as well as elevator shafts, would allow the unrestricted spread of smoke and toxic gases to upper floors. (San Francisco Fire Chief Emmet Condon, testimony before the California Legislature, Joint Committee on Seismic Safety, 1972)

Thus, stairways must remain functional following earthquakes due to the secondary fire hazard. The integrity of exit enclosures against smoke and fire must be preserved to protect lives should fire break out following the earthquake. And repair of damaged enclosures must restore the code-required fire resistance for future emergencies.

2.5 Concluding Remarks

As complex assemblies of substructures, enclosures, components, and equipment, stairways have exhibited a great variety of responses to seismic shaking. Their performance is related to their interactions with the primary structural system and other building components, occasionally resulting in unanticipated damage. This may occur due to poor design, improper location, lack of analysis, weak connections, or faulty construction. The damage, however, is significant because the essential role of stairways as vertical emergency exits is impaired, jeopardizing the safety of building occupants and rescue workers.

In view of the poor performance of various components of many stairways in damaging earthquakes, it is evident that more attention must be paid to stairway systems to reduce adverse effects on structural systems and emergency functioning. Stairways are designed in accordance with building code egress regulations, are located to meet architectural planning needs, and may involve structural engineering of enclosure walls and stair flights. These various aspects must be well-coordinated, and the design intent must be carried through in construction. Awareness of the range of prior damage can guide the design of stairways in new buildings, as well as the rehabilitation of stairways in existing buildings, to improve the seismic resistance of the entire exitway system.

3. SEISMIC CODE REQUIREMENTS FOR STAIRWAYS

Design and construction of buildings in U.S. cities, as well as in most cities of the world, are controlled by standards or codes. These codes

> ...provide minimum standards to safeguard life or limb, health, property and public welfare by regulating and controlling the design, construction, quality of materials, use and occupancy, location and maintenance of all buildings and structures within [their] jurisdiction.... Uniform Building Code 1979, Sec. 102)

In regions where potentially destructive seismic shaking can occur, the building code should incorporate earthquake resistant design and construction regulations. The need for introducing appropriate earthquake resistant regulations in building codes in high risk earthquake regions, and the need for enforcing them, has been demonstrated clearly by the performance of buildings during recent moderate and severe ground shakings (Housner, 1979; Bertero and Shah, 1982).

In view of the necessity of regulations and the importance of stairways in multi-story buildings, the following questions arise: Do present U.S. building codes incorporate sound seismic resistant design and construction regulations for stairways? Do any foreign building codes incorporate such regulations? What provisions for stairways should an ideal seismic resistant design and construction code contain?

3.1 Model Code Provisions for Stairways

A model code for seismic resistant design and construction of building stairways could be outlined in five sections: (1) definition of terms and statement of the functions of stairways, (2) conceptual design guidelines, (3) regulations regarding the seismic resistant analysis and design of stairways, (4) precise specifications regarding detailing and construction, and (5) problems of hazard and evaluation and hazard mitigation of existing stairways.

3.1.1 Definition and Function of Stairways

The model code should present concise definitions of terms relating to the description and functions of stairways. Structural and nonstructural components should be identified, and service and emergency functions outlined.

Stairways provide essential exit paths during fires as well as during earthquake evacuation and rescue operations. Severe ground shaking can trigger the concommitant hazard of fire. Consequently, in seismic regions the code should contain sound regulations to ensure the integrity of stairways for the combined actions of earthquake and fire. Protection from fire alone under normal service conditions is not enough.

3.1.2 Conceptual Design Guidelines for Stairways

The model code should provide conceptual design guidelines that relate to both exit safety and structural considerations.

(a) Exit Safety Guidelines: Guidelines related to fire emergency evacuation are included in most modern building codes. They should be reviewed and modified to bring seismic safety issues forward.

(b) Structural Guidelines: To aid both the architect in the early planning stages of design and the engineer in the later development phases of design, structural guidelines should cover the following aspects:

(1) Integration versus Isolation: Advantages and disadvantages of integrating or isolating stairways from the primary structural system of the building should be reviewed.

(2) The effects of stairway "configuration" (i.e., the distribution and number of stairways in plan, and the form and relation of the stairways to the primary structural system in section) on the overall behavior of the primary structural system should be reviewed. The importance of stairway-structural interaction should be emphasized.

Guidelines and examples of preferred solutions should be provided.

(3) Materials and Construction: Guidelines should cover the selection of materials that will satisfy both fire and seismic resistant requirements.

(4) Effect of Stairways on Local Behavior: The code should review the effects of stairways on the local behavior of structural as well as nonstructural components to which they are connected or come in contact during seismic excitation. Attention should be called to the most typical causes of damage due to these local effects including (i) the creation of"short columns,"(ii) the creation of "short beams," and (iii) the creation of high local shear stresses in floor diaphragms adjacent to openings and enclosure walls. Guidelines for avoiding or minimizing problems associated with local behavior should be provided, and the need to limit damage in stairways should be emphasized.

(5) Nonstructural Components: Stairway systems are complex assemblages of numerous components structurally coupled through connections and attachments. Guidelines regarding the selection and/or design and installation of these components should be provided. Again, the need to control and limit damage in stairways should be emphasized.

3.1.3 Seismic Resistant Analysis and Design of Stairways

Building codes for regions where seismic risks exist should establish minimum requirements for the structural analysis and design of stairways. These requirements should consider both service load conditions (including effects of ground shaking due to minor-to-moderate earthquakes) and extreme load conditions (due to the probable extreme ground shaking foreseen in the service life of the building). The code should make clear which different loading conditions are to be considered and in what combinations. Provisions for stairways integrated with the primary structural system and provisions for stairways isolated from the primary structural system, should be presented.

(a) Code Provisions for Integrated Stairway Systems: In this case the code should refer directly to code provisions for the primary structural system. The stairways should be designed to resist the forces and deformations induced by specified lateral forces. The code should clearly associate load and load combination requirements with required deflection limitations, ductility requirements, and type of analysis (eg., elastic or inelastic) to be used in evaluating member forces and deformations. (Codes, in the past, have specified seismic forces without making clear whether these forces are: (i) the real forces expected to be developed in the structure, (ii) based upon assumed elastic behavior, or (iii) specified assuming that a certain amount of input energy will be dissipated through inelastic response.) Load and load combination specifications should represent, as much as possible, realistic conditions. Deflection limitations (or appropriate limitations on member deformation or distortion) should be specified to ensure control of damage. It may also be necessary for the code to provide guidance on acceptable methods of analytically modeling the contribution of stairways to stairway/structure systems response.

(b) Code Provisions for Isolated Stairway Systems: Code provisions for the design of isolated stairway systems should include regulations regarding the analysis of the primary structural system to determine expected (realistic) system deformations that must be accommodated by the stairway system, and regulations pertaining to investigations needed to demonstrate that the proposed isolation technique will indeed accommodate the predicted deformations. Regulations for the analysis of the primary structural system should clearly establish acceptable means to model the seismic loadings and analytical methods to be used in evaluating the response of the system to these loads.

The regulations pertaining to the investigation of proposed isolation techniques should establish acceptable analytical methods and testing standards to evaluate the effectiveness of the proposal, with specific recommendations for the stairway structural system and nonstructural components.

Attention must be given to defining the meaning of isolation and to establishing acceptable isolation limits. For some isolation techniques physical separation will prove sufficient. For isolation techniques that seek to limit the stiffness contribution of the stairway structural system to the primary structural system through the use of energy dissipating connection details, isolation limits based upon physical separation have little meaning and would tend to discourage their use. Ideally, isolation limits should be based upon a dual measure of the degree of stiffness contribution and the ability to dissipate energy stably, although it may prove impractical to do so.

3.1.4 Detailing and Construction of Seismic Resistant Stairways

The model code should set forth specific provisions regarding detailing and construction of the components of stairway systems. Recognizing the need to maintain the integrity of stairways in extreme events, these details should ensure the reliable performance of the stairway systems during the probable extreme ground shaking that can occur in the service life of the building. Experience indicates that detailing between landings and their supports, and detailing between stair flights and their landings (particularly in reinforced concrete), demand the most careful consideration.

3.1.5 Existing Stairways: Hazard Evaluation and Mitigation

In many cities the majority of buildings have been designed and constructed under the provisions of codes which did not contain sound seismic specifications for stairways or the building structural systems. After severe earthquakes one of the most pressing problems is the rehabilitation of damaged stairways. The model code should provide guidelines for identification of potentially hazardous stairways in existing structures, for evaluation of the degree of hazard, and for mitigation of these hazards. Separate guidelines are needed for post-earthquake emergencies and for non-emergency upgrading. Again, integrated and isolated stairways and stairway modification techniques should be distinguished.

3.2 Present U.S. Seismic Code Regulations for Stairways

Although many cities have their own building codes, most of these codes follow very closely the regulations contained in the Uniform Building Code (UBC). Recently, in 1978, the Applied Technology Council published Tentative Provisions for the Development of Seismic Regulations for Buildings (ATC 3-06), which is considered to be one of the most comprehensive documents available regarding seismic regulations. Stairway provisions in these two documents are reviewed and discussed below.

3.2.1 The Uniform Building Code

The Uniform Building Code (UBC), published by the International Conference of Building Officials, is the technical basis for construction regulations in most seismically active regions in the United States. Its earthquake regulations are based largely on recommendations of the Structural Engineering Association of California (SEAOC), and undergo periodic revisions reflecting improved understanding of the effects of earthquakes on structures and components. Foreign countries look to these provisions when formulating their own seismic codes. The important building codes of Los Angeles and San Francisco, and portions of the California Administrative Code governing the construction of public buildings in California, are strongly influenced by the UBC. Revised editions of the UBC are issued approximately every three years; the 1979 edition is used in this report.

The majority of UBC requirements for stairways relate to their function as exits, as detailed in Chapter 33, "Stairs, Exits and Occupant Loads." Based upon floor area and type of occupancy, the number and widths of required exits may be calculated. In most multi-story buildings at least two stairways are required. Limitations on distance of travel to exits, length of dead-end corridors, and minimum separation of exits influence the planning and placement of stairways in buildings. Specifications are given on types and fire-resistance of enclosure walls, and assemblies of materials meeting these ratings are listed (see UBC-79 Chapter 43). Special provisions for high-rise office and apartment buildings are described in UBC Section 1807.

UBC Section 3305 "Stairways" gives requirements for minimum widths of stairways, minimum and maximum dimensions of treads and risers, dimensional requirements for specially-shaped stairways, size of landings in relation to width of stairway, distance between landings, handrail dimensions, interior and exterior stairway construction, stairways to roof and/or basement, minimum headroom, and numbering systems for taller buildings. Most of these requirements relate to egress in general and fire safety in particular. No mention is made of earthquake hazards. The UBC definition of

> EXIT is a continuous and unobstructed means of egress to a public way and shall include intervening doors, doorways, corridors, exterior exit balconies, ramps, stairways, smoke-proof enclosures, horizontal exits, exit passageways, exit courts and yards. (UBC-79, Sec. 3301 (c).)

and

> No obstruction shall be placed in the required width of an exit except projections permitted by this chapter. (UBC-79, Sec. 3301 (i).)

define "EXIT" in such a way that it is usually considered an as-built specification rather than a performance standard which could then be interpreted as a more useful general requirement for both fire and earthquake events.

(a) Stair Construction Materials: Materials are covered in Part IV, "Requirements Based on Types of Construction." Under "Fire Resistive Requirements," five types of construction are distinguished. For Type I and Type II buildings (i.e., of steel, iron, concrete or masonry construction) stairs shall be constructed of reinforced concrete, iron or steel and may have finish surfaces of hard noncombustible materials. Although wood stairs are permitted in some other types of construction, they are not considered in this report.

(b) Stair Design Load Conditions: In Chapter 23, "General Design Requirements," exit facilities including stairways must sustain a uniform load of 100 pounds per square foot, individual stair treads must sustain a concentrated load of 300 pounds, partitions and interior walls (and thus presumably stair enclosure walls) a lateral load of 5 pounds per square foot, and guardrails or handrails (for occupancies over 50 persons) a load of 50 pounds per lineal foot applied horizontally to the top rail.

Stairways are not specifically mentioned in "Earthquake Regulations," Section 2312. Until 1976 a possible interpretation of the code would allow a stairway to be constructed as a "rigid element" designed purposely to fail during an earthquake under the provisions of UBC-76 Sec. 2312 (j) wherein

> Moment-resisting space frames and ductile moment-resisting space frames may be enclosed by or adjoined by more rigid elements which would tend to prevent the space frame from resisting lateral forces where it can be shown that the action or failure of the more rigid elements will not impair the vertical and lateral load resisting ability of the space frame.

Presently, an interpretation of stairways as "rigid elements" would allow:

> Rigid elements that are assumed not to be part of the lateral force-resisting system may be incorporated into buildings provided that their effect on the action of the system is considered and provided for in the design. (UCB-79 Sec. 2312 (e) 4.)

These "rigid element" provisions emphasize the action of the system rather than life safety and consequently could be construed to allow rigid yet brittle stairway elements which would fail during the earthquake in such a manner that the structural system behavior would not be compromised although life safety would clearly be jeopardized. Such an interpretation of the provisions of the UBC-79 would seem to violate the general provision of Section 2312 (a) that

> Every building or structure and every portion thereof shall be designed and constructed to resist stresses produced by lateral forces as provided in this section.

This provision sets an ideal goal which in practice is difficult to achieve.

In 1976 a new regulation was introduced:

> In Seismic Zones No. 2, No. 3 and No. 4 all framing elements not required by design to be part of the lateral force-resisting system shall be investigated and shown to be adequate for vertical load-carrying capacity and induced moments due to 3/K times the distortion resulting from the code-required lateral forces. (UBC-79 Sec. 2312 (j)1. D.)

where K is a factor related to the type of structural system intended, principally, to account for the likely ductility of the system.

These provisions at best are confusing and at worst are mutually inconsistent, incompatible with the general code objective to "safeguard life or limb" (UBC-79 Sec. 102), and not based upon sound investigations into the behavior of secondary and nonstructural elements under realistic seismic excitation. It must be expected that such confusing regulations would lead to poor design, particularly when extended to stairway systems.

The regulations of Section 2312 (j) 1. E. should be changed to clarify that more is involved than just a demonstration that "the action of the more rigid element will not impair the vertical and lateral load resisting ability of the space frame." It should also be demonstrated that the action (or failure) of these "more rigid elements" will not pose life hazards nor impair evacuation or emergency access to the building during and after an earthquake.

(c) Seismic Forces for Integrated Stairway Systems: In those cases where stairways are integrated with the primary structural systems, the stairways and structural systems together must be designed to resist, "in proportion to their rigidies," the

> minimum total lateral seismic forces assumed to act non-concurrently in the direction of each of the main axes of the structure in accordance with the following formula:
>
> $$V=ZIKCSW \qquad [3.1]$$
>
> (UBC-79 2312 (d))

where:

- V = The total lateral force or shear at the base.
- Z = A numerical coefficient dependent upon the seismic zone as indicated in Figures No. 1, No. 2, and No. 3 of UBC-79 Sec. 2312.
- I = The Occupancy Importance Factor as set forth in Table 23-K of UBC-79.
- C = A numerical coefficient related to the dynamic character of the building and the character of likely seismic excitations, as specified in UBC-79 Sec. 2312 (d).
- S = A numerical coefficient related to soil-structure interaction effects, as specified in UBC-79 Sec. 2312 (d).
- W = The total dead load of the building as defined in UBC-79 Sec. 2302, including (where applicable) partition equivalent dead loads specified in UBC-79 Sec. 2304 (d).

For Z and I equal to 1.0 the value of V can vary between:

$$0.094W \leq V \leq 0.186\ W$$

(the product CS is limited to a maximum value of 0.14 and K ranges from 0.67 to 1.33). This design seismic load is distributed over the height of the structure following the provisions of UBC-79 Sec. 2312 (e).

In those systems where the stairway structural systems are designed as the principal lateral load resisting elements (e.g., stairway shear cores), then most of this design load will be resisted by the stairway systems. Design procedures for such cases are well developed and appear to be reliable, although the contribution of the stair flights and landings to the response of the shear-resisting enclosure walls has not usually been considered.

(d) Seismic Forces for Isolated Stairways: No specific recommendations are given for the design of isolated stairways per se. If isolated stairways are interpreted to be a "part or portion" of the total building structure, however, the provisions of UBC-79 Sec. 2312 (g) may be applied:

> Parts or portions of structures, nonstructural components and their anchorage to the main structural system shall be designed for lateral forces in accordance with the following formula:

$$F_p = ZIC_pW_p \qquad [3.2]$$

where:

- F_p = Lateral forces on a part of the structure, in the direction under consideration.
- Z & I = As given above for the primary structure.
- C_p = The horizontal force factor for "parts or portions" as set forth in UBC-79 Table No. 23-J.
- W_p = The weight of the "part or portion" of the structure or nonstructural component.

The value of the importance factor, I, for the anchorage of equipment required for life safety systems is given as 1.5, but other components of the exitway (except in essential facilities and assembly buildings) are given an importance factor of 1.0. The horizontal force factor, C_p, for walls and partitions is 0.3, but no specific factor is given for the components of the stairway system or for their attachment to the main structural system. Taking the minimum value of $C_p = 0.3$ and $Z = I = 1.0$ it can be seen that by considering the stairway as separated, the effective lateral load attributed to the stairway system that must be resisted is $F_p = W_p$, a value that is considerably greater than that which would be considered if the stairway system were designed as an independent structural system (i.e., 0.094 W to 0.186 W;

see the section above where, in this instance, W would be identical to W_p).

(e) Code Specifications for the Nonstructural Components of Stairways: The seismic forces to be considered in the design of the nonstructural components of the stairway system are also given by Eq. [3.2]. As noted by Sakamoto (1978),

> Most methods by which nonstructural elements are at present designed to resist seismic forces specify a seismic (force) coefficient that represents the seismic inertial force due to the acceleration of the element itself, and a seismic (story) drift coefficient that corresponds to unacceptable deformation of the element.

However, as noted by Yancey and Camacho (1978),

> In general, the provisions of the [UBC] do not explicitly account for the effect of the interaction between the structural system and the nonstructural components. The nonstructural component is to be analyzed as a dynamically uncoupled system, with no consideration being given to the interdependence of the two systems.

Both of these authors are generous in their criticism of present methods of analysis of nonstructural component seismic response. Not only is interaction ignored but also the effective lateral load must be considered to be completely fictitious and is likely to be a poor representation of the actual nature of the seismic forces experienced by the nonstructural component in most cases. Therefore, the soundness of the present UBC regulations for the design of nonstructural components is questionable.

(f) Code Regulations Regarding Design, Detailing, and Construction of Stairways: The present UBC code has no regulations or guidelines concerned specifically with design, detailing, and construction of stairways for earthquakes. The designer or builder must interpret the more general provisions of the code and apply them to the specific problem of stairway design. Due to the structural complexity of stairways and stairway supports, such interpretation is not an easy matter. Reinforced concrete stairs and steel stairs have been reliably designed for gravity loads using analytical techniques developed over the past two decades. Whether these or similar techniques can be used for lateral load considerations requires investigation. (Chapter 5 of this report addresses this question in more detail.)

The 1979 Edition of the UBC contains neither guidelines nor specific recommendations for the analysis, design, or construction of stairways for earthquakes. Present specifications for structural and nonstructural components are based on fictitious lateral seismic forces, with assumptions and exceptions that are confusing. Furthermore, an emphasis is placed on providing safety against collapse of the main structural system of the building while failing to give due consideration to those life safety hazards posed by damage to nonstructural as well as structural elements associated with exits and stairways. Changes in this philosophy and formulation of specific provisions for the layout, analysis, design, detailing, and construction of new stairway systems as well as seismic safety evaluation and strengthening of existing stairway systems are suggested.

3.2.2 Tentative Provisions for the Development of Seismic Regulations for Buildings, ATC 3-06

Tentative Provisions for the Development of Seismic Regulations for Buildings (ATC 3-06) was prepared by the Applied Technology Council in association with the Structural Engineers Association of California and published in 1978. The result of several years' study by teams of multidisciplinary experts, it is the most comprehensive document of its kind available. Although unlikely to be adopted into code, its recommendations have established the basis upon which modern seismic codes will be developed and as such it is an important document in the field.

While stressing life safety,

> Life safety in the event of a severe earthquake is the paramount consideration in the design of buildings. (ATC 3-06),

ATC 3-06 also recognizes that criteria should be available to designers for the design of a facility (e.g., essential or critical facility) that will remain operational during and after an earthquake. To achieve this the ATC document specifies more realistic seismic forces and more stringent requirements for the amount of maximum acceptable interstory drift of the building's main structural system, than the UBC. In addition, the need to control non-structural damage is recognized and guidelines to do so are offered in Chapter 8: "Architectural, Mechanical and Electrical Components and Systems."

(a) Stairway Structural Systems: ATC 3-06 has no provisions specifically directed to the design of stairway structural systems; therefore the designer must exercise judgment in applying the existing ATC 3-06 provisions to stairway structural system design. Again, the relationship of the stairway structure to the primary structural system should be considered. If integrated structurally, stairway design is controlled by the provisions recommended for the primary structural system. In this respect, the ATC 3-06 Commentary offers some planning guidance, in an indirect way:

> There is a second type of distribution of vertical resisting components which, while not being classified as irregular, does not perform well in strong earthquakes. This arrangement is termed a core-type building with the vertical components of the seismic resisting system concentrated near the center of the building. Better performance has been observed when the vertical components are distributed near the perimeter of the building.

Such cores are typically vertical circulation cores containing stairways and elevators. (It should be added that the vertical components should be distributed symmetrically, with respect to the center of mass of the building, near the perimeter of the building.)

The ATC 3-06 document does not contain specific provisions for the design of stairway systems that are isolated from the primary structural system. However, the ATC 3-06 Commentary, in discussing drift and isolation of nonstructural components, notes,

> Rigid elements, such as stairways or masonry walls, should be given special consideration since not only are they subject to damage and loss of function from structural deformations but also, of equal importance, their stiffness may significantly affect the structural system to which they are connected. In each instance both structural and fire resistance requirements have to be reconciled. (ATC 3-06 Sec. C8.2.4)

Furthermore, in the discussion of the development of performance criteria and Architectural Design Requirements of Sections C8.1 and C8.2, "stairs" are identified as an architectural component, performance standards for "stairs" are outlined based upon occupancy (see Tables C8-1, C8-2, C8-3 & C8-5), and design seismic forces are associated with these performance standards that indicate a concern for the importance of stairways. Yet in the actual provisions of ATC 3-06 stairways are not identified as architectural components, although partitions of stairs and shafts are. This apparent oversight should be corrected.

(b) Nonstructural Components of the Stairways: ATC 3-06 gives specific recommendations for the design of partitions of "stairs and shafts" in Chapter 8: "Architectural, Mechanical and Electrical Components and Systems." The basic formula for the seismic force to be resisted by architectural systems, components and their attachments is given in Section 8.2.2 of ATC 3-06 as:

$$F_p = A_v C_c P W_c \qquad [3.3]$$

where:

- F_p = The seismic force to be applied to a component of a building or to equipment, at its center of gravity.
- A_v = The seismic coefficient representing the Effective Peak Velocity-Related Acceleration as determined in Section 1.4 of ATC 3-06.
- C_c = The seismic coefficient (dimensionless) for components of architectural systems as given in Table 8-B, ATC 3-06.
- P = Performance criteria factor (dimensionless) as given in Table 8-A, ATC 3-06.
- W_c = The weight of a component of a building or equipment.

Table 8-B, ATC 3-06, sets C_c = 1.5 and P = 1.5 ("Superior") for stair partitions in buildings of Seismic Hazard Exposure Group III (i.e., essential facilities such as fire, police, and medical facilities) and for buildings of Group II (i.e., with occupants in large numbers or of limited movement) over 4 stories or 40 feet tall. For other buildings, the performance criteria factor, P, is set equal to 1.0 ("Good") while C_c remains at 1.5. The performance criteria factor of 1.5 ("Superior") is meant to achieve a design goal of only cosmetic damage and no loss of fire protection due to an earthquake. Concern about stair enclosure failures is expressed by limitations placed on out-of-plane bending of brittle materials (Section 8.2.5, ATC 3-06),

> Transverse or out-of-plane bending or deformation of a component or system composed of basically brittle materials ... shall not exceed the deflection capability of the material.

although specific brittle materials are not identified nor is their "deflection capability". These requirements are established for "partitions" of "stairs and shafts," but there are no requirements given specifically for stairs and landings.

It is of interest to compare the design seismic forces for partitions of stairs and shafts as required by present UBC provisions [Eq. 3.2], with those required by ATC 3-06 [Eq. 3.3]. For an essential facility located in a region of highest seismic risk (Zone 4), the UBC-79 provisions would require a lateral force

$$F_{p_{UBC}} = 1 \times 1.5 \times 0.3 \times W_p = 0.45\ W_p \qquad [3.2']$$

while the ATC 3-06 would require a lateral seismic force

$$F_{p_{ATC}} = 0.4 \times 1.5 \times 1.5 \times W_c = 0.9\ W_c \qquad [3.3']$$

The design load specified by the ATC is seen to be twice that of the UBC. Since the UBC load is a service limit-state condition while the ATC load is a first-yield condition, these design loads can not be compared directly. For a determinately supported component wherein the allowable material strength is equal to one half the yield strength, then the UBC and the ATC provisions will be equivalent. For the more general, and more typical, case the provisions will not be equivalent.

Although the ATC 3-06 recommendations include many new concepts and procedures regarding the seismic design, construction and maintenance of buildings, and is a welcome step forward toward the formulation of an ideal seismic code, it does not contain clear guidelines or provisions for the design, construction, and maintenance of stairways.

3.3 Present Foreign Building Code Regulations for Stairways

Information on seismic provisions for stairways in building codes of other countries has been obtained from Earthquake Resistant Regulations, a World List - 1980, published by the International Association for Earthquake Engineering. This list is useful for comparing requirements and design emphases from other regions subjected to earthquakes. Due to the concentration of this list on seismic regulations, provisions for fire and life safety aspects of stairways are not included. Code provisions have been grouped and summarized under the desirable features of conceptual guidelines and specific recommendations for seismic resistant design and construction of stairways.

3.3.1 Guidelines Regarding Conceptual Design of Stairways

(a) Algeria: In the Recommendations Relative to Building Construction in Regions Subject to Earthquakes developed in 1955 by the French authorities, it is advised:

> To prevent damages that will impair rapid evacuation [exiting] in case of ground shaking. Each stair flight must constitute a rigid system well tied to the landings and to the structure.

Although this general recommendation was formulated in 1955, the El-Asnam Earthquake of 1980 showed that in most cases this recommendation was not enforced and/or was ignored.

(b) Canada: The National Building Code of Canada, 1980 does not contain specific recommendations for the seismic design of stairways, although the following provisions are pertinent to stairway design.

> 4.1.9.2.(1) Lateral deflections of a storey relative to its adjacent storeys shall be considered in accordance with accepted practice.
>
> (2) Lateral deflections of a storey relative to its adjacent storeys obtained from an elastic analysis using the loads given in Sentence 4.1.9.1.(12) [formulae for the distribution of the total lateral seismic force] shall be multiplied by 3 to give realistic values of anticipated deflections.
>
> (3) All portions of the structure shall be designed to act as integral units in resisting horizontal forces, unless separated by adequate clearances which permit horizontal deflections of the structure consistent with values of deflections calculated in accordance with Sentence 4.1.9.2.(2).
>
> (4) The nonstructural components shall be designed so as not to transfer to the structural system any forces unaccounted for in the design, and any interaction of rigid elements such as walls and the structural system shall be designed so that the capacity of the structural system is not impaired by the action or failure of the rigid elements.

Regarding these general recommendations, one Canadian engineer has noted that,

> The damage-control provisions...are contained in a small section (4.1.9.2) near the end of the seismic loading provisions. The sentences of this section include some general statements on: the need to consider lateral drift, the need to provide clearances for non-integral structural units, the need to consider load transfer to non-structural components....It should be noted that all these needs are expressed in very general terms with no numerical or quantitative limits stated....The actual level of protection is almost entirely dependent upon the designer's concerns (and presumable the owner's as well). (Heidebrecht, 1979)

(c) People's Republic of China: Aseismic Design Code for Industrial and Civil Buildings, TJ 11-78, 1979 contains some general recommendations that refer specifically to stairways. Article 39:

The staircase should not be placed in the first bay at the end of a building....

Cantilever stair steps and precast steps with their vertical ribs inserted into walls shall not be used.

Unreinforced brick masonry fenders [walls] shall not be used.

(d) India: Indian Standard IS: 4326-1976, Code of Practice for Earthquake Resistant Design and Construction of Buildings, 1976 has the following section devoted to stairways:

4.5 Staircases

4.5.1 The interconnection of the stairs with the adjacent floors should be appropriately treated by either providing sliding joints at the stairs to eliminate their bracing effect on the floors or the design and construction should be such as to afford adequate strength to the stairs to transmit shear between the adjacent floors. Large stair halls shall preferably be separated from the rest of the building by means of separation or crumple sections.

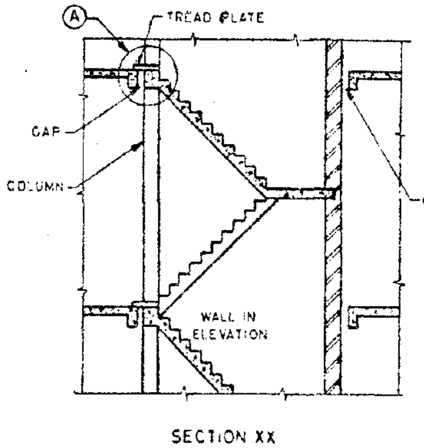
4.5.1.1 Three types of stair construction may be adopted as described in 4.5.2, 4.5.3 and 4.5.4.

4.5.2 Separated Staircases--One end of the staircase rests on a wall and the other end is carried by columns and beams which have no connection with the floors. The opening at the vertical joints between the floor and the staircase may be covered either with a tread plate attached to one side of the joint and sliding on the other side, or covered with some appropriate material which could crumple or fracture during an earthquake without causing structural damage. The supporting members, columns or walls, are isolated from the surrounding floors by means of separation or crumple sections. A typical example is shown in [Fig. 3.1 (a), (b), (c)].

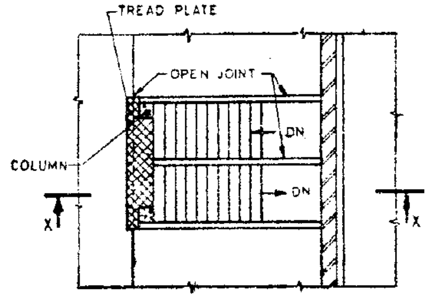
4.5.3 Built-in Staircase--When stairs are built monolithically with floors, they can be protected against damage by providing rigid walls at the stair opening. An arrangement in which the staircase is enclosed by two walls is given in [Fig. 3.1 (d), (e), (f)]. In such cases the joints as mentioned in 4.5.2 will not be necessary.

4.5.3.1 The two walls mentioned in 4.5.3 enclosing the staircase shall extend through the entire height of the stairs and to the building foundations.

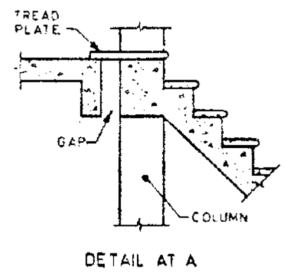
4.5.4 Staircases with Sliding Joints--In case it is not possible to provide rigid walls around stair openings for built-in staircase or to adopt the separated staircases, the staircases shall have sliding joints so that they will not act as diagonal bracing.



(a) Separated staircase



(b)



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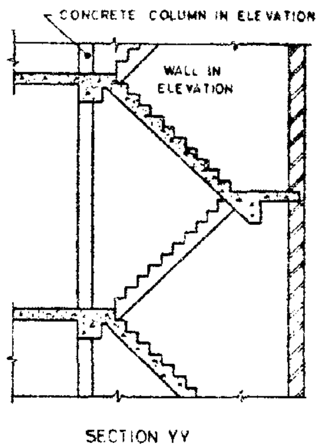
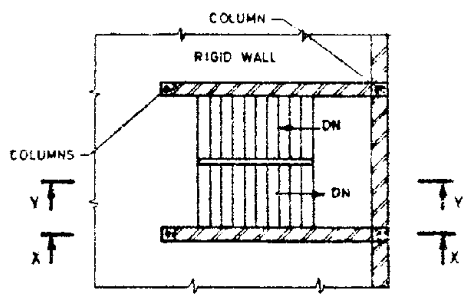
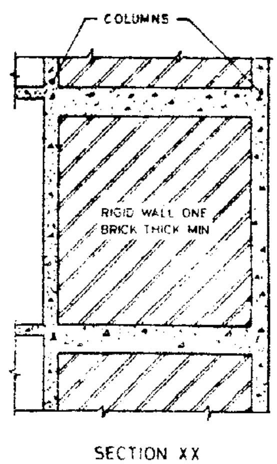


(d) Rigidly built-in staircase



(e)



(f)

Fig. 3.1 Staircase details, from Indian Code of Practice for Earthquake Resistant Design and Construction of Buildings.

The Indian Code is the only code that specifically describes different types of stairways for construction in seismic regions. It emphasizes the need to avoid the stair flight acting as a diagonal bracing member of the structure. While this is generally a sound idea, particularly when the main structural system is very flexible (as in ductile moment-resisting space frame systems), it may not be necessary where the main structural system is very rigid (as in wall or wall-frame construction). As pointed out previously, estimating the necessary gap for separated staircases presents a problem. For the recommended built-in staircase [Fig. 3.1 (d), (e), (f)],it is necessary to construct rigid walls that will resist earthquake effects without producing debris that could cover the stairs. The code indicates that brick walls are adequate; the authors believe that if brick walls are used they should be properly reinforced (one effective way has been recommended by Brokken and Bertero, 1981) or the masonry panels should be small, not larger than 2 x 3 m, and properly confined by horizontal and vertical reinforced concrete members. Furthermore, if the designer elects to use a built-in stairway, the stiffness contribution of the walls to the structure as a whole must be considered.

(e) Indonesia: The Manual for the Design of Normal Reinforced Concrete and Reinforced Masonry Structures and Commentary of the Indonesian Earthquake Study requires the separation of stairways from the structure, unless the stairways can "accept interstorey deflections of four times those calculated... without being damaged and without affecting the structure" or if the calculated deflections are small in relation to storey height. Stairs and their enclosing shaft walls are assigned a performance coefficient in the calculation of applied seismic loads.

(f) New Zealand: The Code of Practice for General Structural Design and Design Loadings, NZS 4203: 1976, does not contain direct recommendations for the design and construction of stairways. The code is based on a philosophy, however, that definitely guides such design. This code contains a series of provisions to reduce the nonstructural damage during earthquake shaking, reflecting the growing concern for economic losses due to nonstructural damage.

Portions of New Zealand Standard NZS 4203:1976 were developed from years of study of the effects of nonstructural damage. Particular attention was paid to the interaction of secondary elements with more flexible primary structures, and the effects of damage on fire resistance capabilities, emergency functioning, safety of building occupants, and ease of repair. Separation of nonstructural elements from the primary structural system has become a guiding philosophy of design in New Zealand. Therefore, this new standard contains specific provisions regarding the evaluation of deformations due to earthquake effects. The main requirements concerning the computation of deformations, as well as the corresponding commentary, are reproduced below.

NZS 4203:1976 - COMMENTARY	NZS 4203:1976 - REQUIREMENTS
	3.8 DEFORMATION DUE TO EARTHQUAKE LOADS
	3.8.1 Computed deformations
C3.8.1.1 The deformation of the structure should be computed on the assumption that its members are highly stressed just prior to the onset of yeilding. Any rational method including all significant parameters contributing to deformations, such as the extent of cracking in reinforced concrete frame members, the deformations of joint zones and the cracking of cover concrete in structural steel frames, and the like may be used. Alternatively, for ductile frames in reinforced concrete or structural steel the following simplified procedure is acceptable. *Reinforced concrete: Use 0.75 gross uncracked moment of inertia of section.* *Structural steel: Use 4/3 times the computed deformations ignoring joint deformations and cracking of cover concrete.* *In the case of T or L beams, half the width of the reinforced concrete slab allowed by the relevant material code for gravity loads may be included in the moment of inertia computation.* *For shear walls simplified procedures are not available but an upward adjustment similar to that for frames is acceptable because of the relative conservatism of the modification factor for these structural types.*	3.8.1.1 For the purposes of this clause, deformations shall be those resulting from the application of the horizontal loads specified in section 3.4 increased by the modification factor ν as given by clause 3.8.1.2. Alternatively, deformations may be derived using the methods of section 3.5 and increased by the modification factor ν as given by clause 3.8.1.2.

C3.8.1.2 Computed deformations vary proportionally with the value of C_d. Compared to the value of C_d derived from S = 1, M = 1, considerable reductions result for structures with the same importance and located within the same seismic zone, for example, M = 0.8 (structural steel) S = 0.8 (adequate redundancy) and up to 10 percent reduction in some cases where a dynamic analysis has been made. The justification for reductions in strength does not apply to deformations. For those systems for which the principle of equal displacements for the inelastic system and elastic system with the same initial stiffness applies, neither reductions nor increases in C_d values will affect the total displacement in an earthquake. The modification factor is aimed at achieving this, that is, separation requirements proportional to CI.

Designers should be aware that for structures dissipating energy in a ductile flexural mode the separation requirement of this standard gives average damage protection to a class III building with 5 percent damping in seismic zone A at levels of motions up to one-third 1940 El Centro N–S only. Furthermore, buildings where energy dissipation tends to be localized in some storeys are prone to large deformations. Thus wherever practical a greater degree of separation should be provided. Measured responses in New Zealand and overseas confirm the large deformations suffered by modern framed structures owing to their low damping characteristics.

To account for the different characteristics of structures coming under items 6 and 7 of table 5 a differing formulation for the modification factor has been used. Excepting in cases where these structures suffer early stiffness degradation, the separation required by this standard can be expected to provide a relatively better degree of protection for them than for ductile frames. The inclusion of structures coming within item 7 of table 5 in the same category as those of item 6 is justified by their higher displacement response but allowing at the same time for their higher S value.

The deformation modification factor for prestressed concrete structures is based on a limited amount of work done to date on their response, and this provision corresponds to a 40 percent increase relative to reinforced concrete structures with the same initial stiffness. In conjuction with the material factor M = 1.2 for prestressed concrete the same level of element and building protection can be expected to result.

3.8.1.2 The modification factor ν for the computed deformations as given by clause 3.8.1.1 shall be as given by table 10, provided that the value of C_d shall be taken as KC_d in accordance with clause 3.5.2 when that is the value used in the computation of deflections.

3.8.1.3 For the purposes of this clause, deformations may be calculated neglecting foundation rotations but an appropriate allowance shall be made for cracked concrete sections.

Table 10

MODIFICATION FACTOR ν FOR COMPUTING DEFORMATIONS DUE TO EARTHQUAKE LOADS

Item	*Type of structure*	ν
1	Structures dissipating seismic energy by ductile flexible yielding (items 1, 2, 3, 4, 5, and 8 (b) of table 5) Small buildings of the type specified by clause 3.4.8.3.1	$\frac{2.0\,CI}{C_d}$
2	Shear walls, buildings with diagonal braces capable of plastic deformation in tension only (items 6 and 7 of table 5)	2.0
3	Structures in which prestressed concrete elements form the primary horizontal load resisting system Small buildings designed by the elastic response design procedure specified by clause 3.4.8.2	$\frac{2.8\,CI}{C_d}$

*3.8.2 Building separations

3.8.2.1 Each building separated from its neighbour shall have a minimum clear space from the property boundary, other than adjoining a public space, either 1.5 times the computed deflections as given in clause 3.8.1 or 0.002 times its height, whichever is the larger, and in any case, not less than 12 mm. Parts of buildings, or buildings on the same site separated from each other shall have a minimum clear space from each other either of 1.5 times the sum of their computed deflections as given by clause 3.8.1, or of 0.004 times their height whichever is the larger and in any case not less than 25 mm. Separation spaces need not extend into the foundations except where the Engineer may direct.

* As altered by Amendment.

C3.8.2.2 The provisions of clauses 3.8.2, 3.8.3 and 3.8.4 are intended to avoid major structural damage caused by hammering of buildings and interference between structural and non-structural elements; they are also intended to reduce non-structural damage and the resulting hazard to occupants. Panic amongst occupants caused by large building sway has been a further consideration.

Earthquake damage in the Anchorage earthquake (failure of precast claddings and windows) and the Caracas earthquake (serious structural failure due to weak non-structural hollow clay partitions) required a review of separation requirements.

Non-separation of elements is now permitted only in very rigid buildings. The practical difficulties and the expense of large separations have not been ignored, and the required minimum separation distances are significantly smaller than the deformations that could result from the imposed forces of a major earthquake.

3.8.2.2 Separation spaces shall be cleared of construction debris and detailed so as to remain clear during normal use. Construction tolerances shall make allowance for the clear space provisions. Space coverings shall be durable and shall allow three-dimensional movement. Where compressible space fillings are used, specified clearances shall be appropriately increased and the forces resulting from the compression of the filler material allowed for in the design.

***3.8.3 Inter-storey deflections**

3.8.3.1 Inter-storey deflections shall be computed in accordance with clause 3.8.1 between two successive floors. The inter-storey deflection of any point on the floor shall be taken as the horizontal displacement of that point relative to the corresponding point on the floor below.

3.8.3.2 The ratio of inter-storey deflection to storey height shall not exceed 0.0006 of the storey height where non-structural elements are not separated as specified in clause 3.8.4 and not more than 0.010 of the storey height in any case.

C3.8.3 The intention of clause 3.8.3 is to determine a building deformation that is significant in relation to damage to the non-structural elements listed in clause 3.8.4. In general the inter-storey deflection as defined by clause 3.8.3.1 may be taken as an adequate measure of the damage potential to the listed elements.

In special cases, for example where the elements are located in bays containing members subject to large axial deformations, other criteria may apply, such as where elements are located in bays adjacent to relatively slender shear walls. In other cases the deformation of horizontal members may also need to be considered.

A class III reinforced concrete shear wall building with just sufficient stiffnesses to qualify for non-separation may suffer inter-storey deflections of the order of 3 mm for a storey-height of 3.6 m in a 1940 El Centro N–S type motion if it has 10 percent damping and suffers no damage.

***3.8.4 Separation of elements**

3.8.4.1 Except as provided by clause 3.8.3.2, the following elements shall be effectively separated from the structure in accordance with clause 3.8.4.2.

(a) Elements, such as stairways, rigid partitions, and infillings, that are capable of altering the intended structural behaviour to a significant degree.

(b) Precast concrete claddings and other claddings of similar mass.

(c) Glass windows and other rigid brittle exterior claddings, except in the case of claddings on class III buildings in seismic zone C that in the case of failure cannot fall through a height greater than the storey in which they were installed.

3.8.4.2 Separation provisions required by clause 3.8.4.1 shall allow for the computed deformations as given by clause 3.8.1

C3.8.4 It is at present believed that for some parts of New Zealand the damage risk and life risk resulting from the exclusions contained in clause 3.8.4.1 (c) are acceptable. The effects of more distant earthquakes may make this assumption less valid for structures of a relatively longer period than for those of a shorter period. The mode of failure of windows and other brittle claddings subjected to in-plane loadings is uncertain. If, as they have done in some experimental investigations, they suffer explosive failure this would add to the hazard.

Further investigation of these and other aspects is required. Windows falling the height of only one storey should constitute a lesser direct risk but broken glass in the streets obviously is a hazard to people attempting to leave a building following an earthquake and also to those engaged in rescue operations in general. In seismic zones where moderate earthquakes are likely to occur more frequently, damage control aspects in addition to measures required to limit life risk, require the separation of all exterior brittle elements in all storeys.

Inserts in concrete should be attached to or hooked around reinforcing steel, or otherwise terminated to effectively transfer seismic forces. Required anchors in masonry walls of hollow units or cavity walls should enter a reinforced grouted structural element of the wall.

*As altered by Amendment

DEFINITION OF TERMS USED

Section 3.4: Equivalent Static Force Analysis
Section 3.5: Dynamic Analysis

C = Basic seismic coefficient

C_d = Seismic design coefficient

I = Importance factor determined by the type of occupancy or function of the building

K = Factor by which the values of C are scaled to give the spectrum to be used for the spectral modal analysis of a particular building

M = Structural material factor

S = Structural type factor

V = Modification factor for computed earthquake deformation

Seismic Zones: A (highest), B, C (lowest)

Class III Buildings: Buildings other than public buildings and essential facilities required to be completely functional immediately after a seismic disaster.

As can be seen from clause 3.8.4.1, the NZS 4203:1976 allows non-separation of elements only when the computed drift does not exceed 0.0006 of the storey height. As pointed out by one of the code writers,

> Some field evidence is available to indicate that this provision is reasonable....The effect of the separation provision ... will therefore be to exclude all but very stiff structures. This is well justified not only by the economic consequences of damage...but also because of the obvious life hazard created by non-structural damage. (Glogau, 1976)

In relation to these requirements, considerable research on stairway isolation has been undertaken in New Zealand and several New Zealand engineers have proposed changes in stairway design. These are discussed in Chapter 5 of this report.

(g) Union of Soviet Socialist Republics: In Construction in Earthquake Region Design Code, 1969, Section 3.53, it is stated that,

> The staircases of framed buildings may be designed as built-in units separated storey by storey, without affecting the rigidity of the frame, or as a rigid core designed to take seismic loads; for buildings not more than five storeys high, it is permitted to provide stairs in the form of independent units detached from the frame of the building.

Thus this code allows the practice of stairway isolation.

3.3.2 Code Recommendations Regarding the Design, Detailing and Construction of Stairways.

Very few codes give specific recommendations or guidelines regarding design, detailing and construction of stairways; the following are some codes that do.

(a) Bulgaria: The 1964 Code for Buildings in Earthquake Regions is divided into seven parts, of which Part 3 is devoted to Building-Constructive Indications for Dwellings, Public, Industrial and Agricultural Buildings. Part 3, Section 8, discusses stairways and is reproduced below.

8. Staircases and Partition Walls

8.1 Principally the staircases are constructed and calculated as spatial constructive systems. In seismic regions of VII and VIII degree fixing of the steps in the walls is allowed if their length is up to 1.20 m; For larger length the fixing is performed by belts calculated for torsion at ordinary loading. [Seismic region IX has the highest value. Belts are "anti-earthquake reinforced concrete belts."]

When the steps are constructed and are calculated as consoles the longitudinal distributing reinforcement must not be less than 5 ϕ 6.5 mm/m. It must pass continuously through the staircase shoulder and the landings, and must be anchored in the transverse beams of the staircase.

8.2 When the walls are brick-layed, the beams of the staircase landings must lie at least 25 cm in the wall.

(b) People's Republic of China: The <u>Aseismic Design Code for Industrial and Civil Buildings</u>, Chapter 4, is devoted to Aseismic Constructive Requirements. Article 39 requires that:

Where design intensity is 9 [as in regions of high seismicity], 2 ϕ 6 steel bars should be laid along the height of the wall at every 50 cm spacing in the transverse and longitudinal staircase walls at the top story, as for the other stories, a 6 cm thick mortar belt may be placed in the wall near the stair landing or half height of the stories. The grade of mortar shall not be less than 50 and 2 ϕ 10 steel bars shall be installed.

Where design intensity is 8 or 9, the supporting length of girders at the quoins [corners] of the interior walls at the staircase and lobby shall not be less than 50 cm and the girders shall be tied up with the ring beam.

A reliable connection should be ensured between precast stairs and beams of landing slabs.

(c) Union of Soviet Socialist Republics: The <u>Construction in Earthquake Regions Design Code, 1969</u>, Chapter 3 on Residential, Public and Industrial Buildings and Structures, has the following section wherein specific recommendations are given for design, detailing and construction of stairways:

3.53 It is recommended to use prefabricated reinforced concrete stairs assembled from maximized units. Stair landing beams should be embedded into the masonry to a depth of not less than 25 cm and anchored. It is necessary to specify how treads, stringers and prefabricated flights shall be secured and how the stair landings shall be joined to the floor slabs. The use of treads cantilevered out from masonry walls is forbidden. Door and window openings in masonry staircase walls shall normally be framed in reinfoced concrete, when the seismic design rating is 8 or 9 [high earthquake intensity ratings].

3.4 Concluding Remarks

The comparison of earthquake damage observed in cities where no seismic codes were enforced with that observed in cities where sound seismic resistant design regulations have been developed and enforced provides a clear demonstration of the need to introduce such regulations in building codes in regions of moderate to severe seismic risk. Within these seismic resistant codes, special consideration should be given to stairways both because they often have the potential to significantly affect the seismic response of the building as a whole and because they are an essential building component needed for emergency exiting and access during and after an earthquake. An outline of desirable code provisions for the seismic resistant design and construction of building stairways has been presented and the relevant provisions of several seismic resistant codes have been reviewed in this chapter.

Review of existing national and foreign seismic code specifications reveals that very few building codes directly refer to the problem of the design of stairways. Rather, stairways are implicitly included in those provisions addressing the more general problem of seismic resistant design of architectural and nonstructural components, wherein a primary emphasis is placed upon limiting interstory drifts (or the effects of interstory drift) and a secondary emphasis is placed upon the actual seismic response of the component in question. Typically, the actual response is estimated by an equivalent static lateral load that does not rationally account for interaction with the primary structural system, although in some codes a higher force factor is required for those elements (e.g., stairway enclosure walls) considered as part of the building's life safety system. While these general provisions may be suitable for most nonstructural building components, it is the opinion of the authors that the provisions are not sufficiently specific and detailed for the important emergency-function building components that make up the stairway systems.

Some codes provide details of stair attachment and reinforcing, and forbid or discourage problematic cases such as cantilevered stairs. A few codes give specific recommendations regarding the architectural and structural conception of stairways. At present the code recommendations appear to be directed toward either separating stairways from the primary structural system or integrating them while stiffening and strengthening their enclosure. Code recommendations relating to integration strategies need to place greater emphasis on means of estimating structural behavior (analysis) and designing the integrated stairway structure/primary structure system. The strength and ductility of connections, particularly of flights to landings, supporting members, and/or enclosure will most certainly demand careful consideration.

4. ARCHITECTURAL DESIGN OF STAIRWAYS FOR EARTHQUAKES

Architects frequently assume primary responsibility for the conceptual design and functional organization of a building project, based on contractual relations with the building owner/client. Preliminary decisions about general circulation patterns are often made before the schematic design is discussed with the structural engineers. Distribution and arrangements of stairways result from considerations for spatial organization, internal circulation routes, functional layout, and emergency egress requirements. In addition to enclosed exit stairways, a building may contain one or more monumental open stairways, one or more elevators, service shafts, and external stairways. Differences in stair design reflect their architectural importance and intended frequency of use, as well as the calculated number of users for emergency egress.

> Architects should study and understand antiseismic design so that they may provide basic structural concepts that permit sound engineering. Furthermore, in the design of an infinity of non-structural details the architect must incorporate seismic considerations. For instance, more attention must be given to stairs and elevators in tall buildings. Both are vulnerable to heavy damage during a quake, consequently making it unacceptably difficult for people to escape even though the building structure itself is unharmed. (Duke, 1973)

Architects necessarily make structural decisions, with or without structural consultation, which affect the primary structural frames and/or shear walls and the secondary elements of cores, shafts and stairways. Architects are also involved with the building owner in economic consultations which determine choices of materials, construction methods, and allowable levels of damage risk.

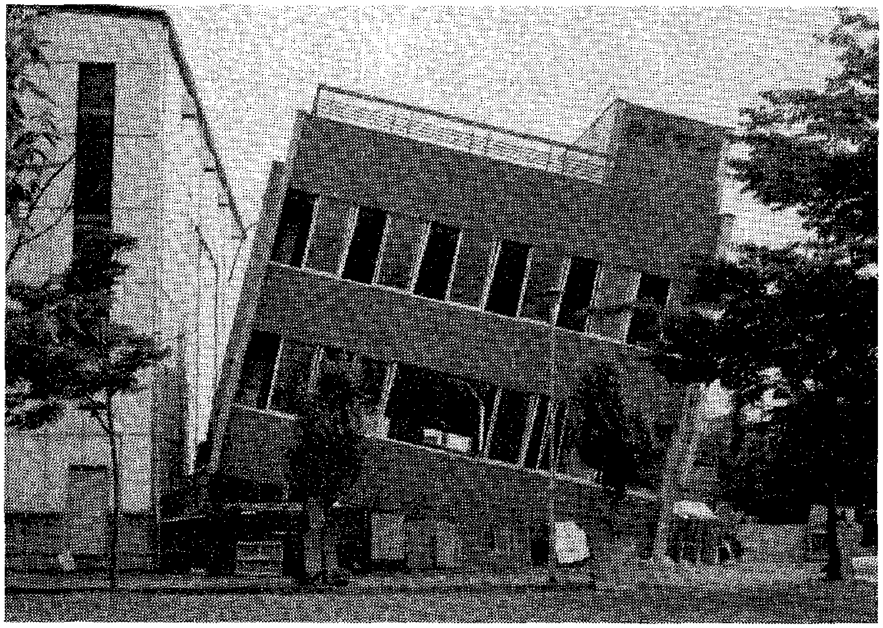


Fig. 4.1 Torsional effects of a heavy eccentric stairwell, Obisan Building, 1978 Miyagi-Ken-Oki Earthquake. (Photo courtesy of Peter Yanev.)

4.1 Preliminary Planning and Design of Stairways

A preliminary guide to planning and locating exit stairways is the local building code. (The Uniform Building Code is reviewed in Section 3.2.1 of this report.) Qualitative and quantitative requirements may be indicated for stairway width and step dimensions, enclosure materials, door characteristics, minimum number of exits, minimum separation of exits, and maximum travel distances to exits. The nature of exit systems is typically expressed in terms of fire emergencies, especially with regard to fire resistance ratings of enclosure assemblies and provisions for ventilation. Since performance requirements for exit systems following earthquakes may not exist, the architects must rely upon judgment and experience.

For stairway systems intentionally designed to be part of the primary seismic resistant system, the number and location of stairway shafts within a building inevitably become important planning decisions in relation to both the spatial and the structural layouts. Overall structural considerations may require changing the number of these shafts, or repositioning them, to provide better stiffness and/or mass distribution. The stairway shafts (and other service cores) should be distributed in plan to avoid torsional effects. This goal encourages the use of many shafts, rather than few, distributed remotely and in such a manner that the stiffness distribution of the resistant elements (shafts and any other vertical elements) balances the mass distribution in plan. For a typical rectangular building plan the shafts would be symmetrically distributed. Effects of poor location and distribution of such intentionally structural stairway systems on the actual overall seismic response of buildings are shown in Figs. 4.1 and 5.2. Local structural considerations will help to detect unfavorable locations of these shafts. For example,

> A stairwell or elevator shaft straddling the line of a diaphragm chord will substantially weaken a diaphragm. (Dean & Zacher, 1976).

Similarly, the shaft located at a re-entrant corner in the building plan may be expected to cause distress in the floor diaphragm.

Especially problematic are those stairway systems which act unintentionally as part of the primary structural system and, consequently, result in seismic behavior unanticipated by the designers of the building. As discussed in other sections of this report, such stairway systems may significantly influence the initial elastic response of the building to seismic excitation by their distribution and stiffness, and affect the inelastic response of the building by their number and ductility. This underscores the need for continuing dialogue between the architect and the structural engineer on the location and design of stairway systems so that unanticipated interactions may be avoided.

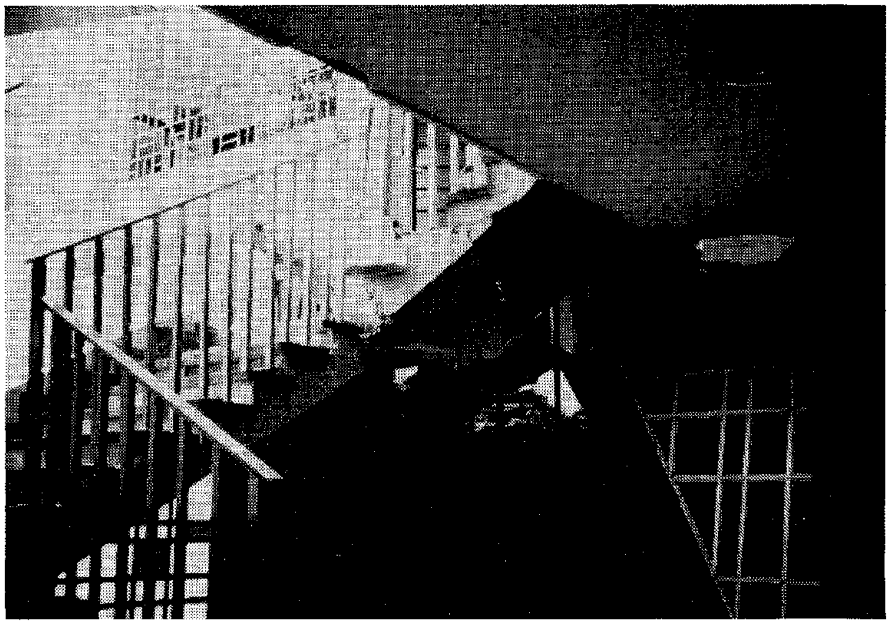


Fig. 4.2 Stair flight damage, San Bosco Building, 1967 Caracas Earthquake. (Photo courtesy of Henry J. Degenkolb.)

4.2 Stair Materials and Details

Due to fire resistance requirements of building codes, stairs in multistory buildings are most frequently made of steel or reinforced concrete. (Section 1.4 of this report discusses conventional stairway design and construction.) For economy, prefabricated steel stairs or steel stringer and concrete tread stairs are often used. Precast concrete stair flights and cast-in-place concrete stairs are common in buildings with rigid structural systems. In many cases the details of construction and installation are left to the stair manufacturer, particularly if standard stairs are specified.

Some architectural and engineering offices have developed in-house stair details which are reused from project to project. The attitude may be that "a stair is a stair" and no special consideration need be given. Some engineering handbooks (see, for example, Gaylord & Gaylord, 1979; Hart, Henn

& Sontag, 1978) show typical reinforcing schemes for concrete stair systems or connections for steel stairs, but few reference books (see Dowrick, 1977, as one exception) relate these details to seismic performance. For example, details reproduced in Fig. 1.2 indicate stair landings at both concrete and steel structural columns, without comment. Figures 2.1 and 2.3 illustrate effects of mid-height column restraint.

> Unfortunately there is little literature available giving specific guidance on aseismic architectural detailing....Virtually no basic research had been done in this area and it appears that architects in earthquake areas to date have largely relied on details considered to be 'good practice', without discussing their experience. We are forced to start almost from square one, observe what goes wrong with architectural details in earthquakes, and try to prevent repetitions. (Dowrick, 1977)

Problems may arise with the implementation of new ideas because "a design can only be effective if it can be constructed" (Bertero, 1979) and if it is actually constructed and maintained as planned. For stairway isolation strategies,

> Provisions for seismic movement involve features that are contrary to normal trade practice. If the site work force do not understand the reasons for some of the details, they are liable to place packers in movement gaps, connect elements that move relative to one another by fixings and lock up sliding joints with sealers. We have adopted the practice in recent jobs of including explanatory notes with the specification, setting out how the various separation provisions are intended to work. (McKenzie, 1977)

Careful detailing and job-site inspections are important to ensure compliance with the design intent.

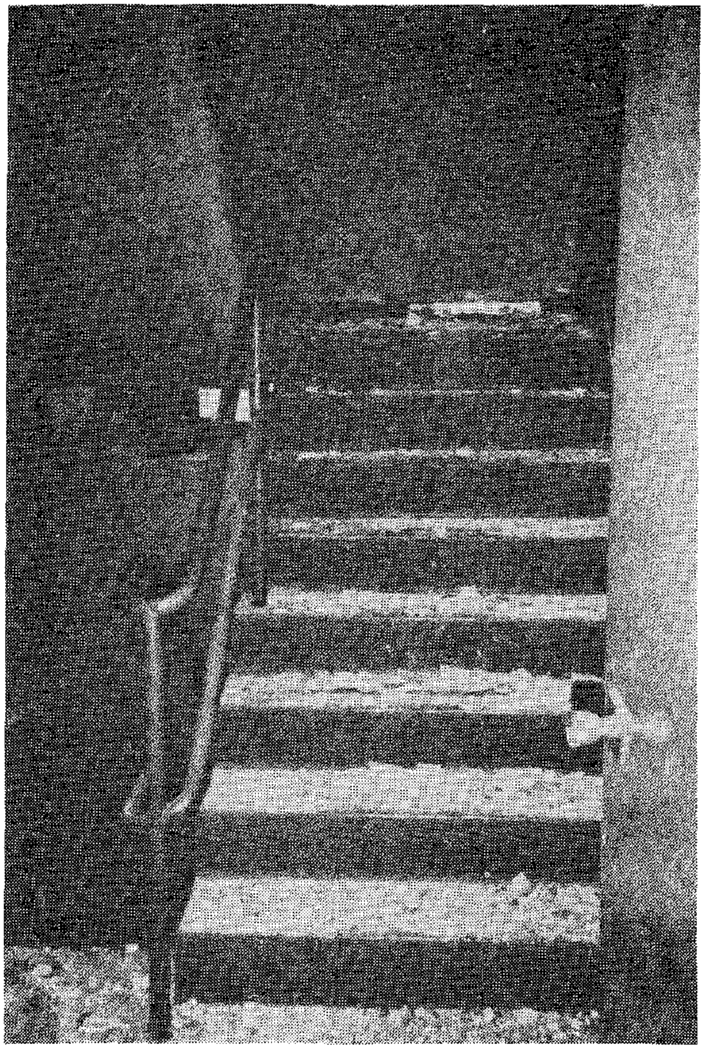


Fig. 4.3 Debris-littered stairway, Anchorage-Westward Hotel, 1964 Alaska Earthquake. (Photo reproduced from The Great Alaska Earthquake of 1964 - Engineering with the permission of the National Academy of Sciences, Washington, D.C.)

4.3 Stair Enclosures

The primary function of stairway enclosure walls and ceilings is protection of building occupants from the hazards of smoke and fire while exiting. Building codes specify the fire resistance required and may indicate assemblies of materials which meet these requirements. Stair enclosure walls may also be designed as shear walls in the lateral force resisting system. In this case the enclosure walls must be considered as part of the primary structural system and must receive special attention from the structural engineer.

Of all the components of the stairway system, the enclosure walls have been subjected to the greatest scrutiny due to their susceptibility to failure during earthquakes and the subsequent life safety hazards. Qualitative recommendations for improved construction practices have appeared after every major earthquake.

> Unreinforced-concrete-masonry units should not be used in any walls, especially not in exit walls....Brittle veneers, such as tiles, should not be applied directly to the inside of concrete stairways. If they must be used, they should be mounted on separate stud walls or furrings. (Ayres, Sun & Brown, 1973)

> If exit corridors of stairs are enclosed by brittle, unreinforced masonry wall elements, the wall elements may become badly cracked in a severe earthquake, particularly those which are tightly enclosed by the structural frame. Sometimes they even appear to explode. This is the type of failure that can occur where earthquake motions are parallel to the walls. Where the earthquake forces are normal to the plane of the wall, the walls will tend to bend as a slab. If they are incapable of taking tension, they could fail in flexure. (Culver, 1975)

Concrete, concrete masonry unit, and hollow tile enclosure walls have been widely used to satisfy building code requirements for fire resistance, although earthquakes have repeatedly demonstrated the extreme life hazard of unreinforced walls. Recommendations for the design, analysis, and detailing of reinforced walls of concrete or masonry have been published extensively and will not be considered here.

Enclosure walls of studs and plaster or gypsum dry wall are also used to meet fire-resistive requirements in multi-story buildings.

> Exit way enclosure walls using metal studs and plaster may have some cracks, but there is a considerable basketing effect so that only small portions would tend to fail....The use of dry wall over metal studs forms a wall that can take some distortion. Some cracks may occur, usually at the dry wall joints and some fastenings may come loose. However, the life risk here is also comparatively low. The fastening and support of the top and bottom tracks is important so that the entire wall will not topple. (Culver, 1975)

> Partition systems fabricated from many components that are mechanically fastened and are allowed to move under seismic conditions usually perform better than partitions of monolithic materials. (Fisher, 1979)

Gypsum shaft wall systems using steel studs and gypsum panels have been developed for high-rise structures in the interests of economy, faster construction time, and reduced weight. In recent years, more attention has been paid to accommodating relative movement between wall panels and the primary structural frame in non-shearwall systems. However,

> In the design of secondary elements supported by a relatively flexible framed structure there are risks of incompatibility between demands for seismic separation to accommodate relative movements and the requirements for fire and smoke stopping, sound attenuation and security. (Allardice, 1977)

Design of stairway systems for the consecutive occurrence of earthquake and fire may require the development of special details.

> To maintain a fire separation around...[a stair detailed not to resist shear nor to stiffen the structure,] we need a soft joint that will allow slippage at the top of the partition. The new fiberglass insulations being marketed as fire stops might be investigated in such a joint. The stair enclosure must also be kept free from columns to prevent racking which would jam exit doors within their frames. Consideration of these criteria will create exit stairs that are quite a bit more elaborate than those we are used to seeing. (Hartray, 1979)

Cracking and minor debris may result from the deformation of reinforced walls, but the life hazards are considerably less than from unreinforced masonry walls. However, outer shells of concrete masonry units have spalled off under seismic motions because the grouted cores had shrunk when drying. Shear cracks or cracks along horizontal construction joints may be more prevalent if the enclosure wall also serves as a structural shear wall. Cracking may also be expected in plaster over lath and at the joints in dry wall panel systems. Economic considerations suggest that more attention be paid to these enclosure walls.

> Often the greatest single item of expense concerning nonstructural damage, is for the repair of cracked plaster in partitions. (Green, 1978)

Data from the 1971 San Fernando Earthquake substantiate this claim (Hart & Stillman, 1972). Cracks in stair enclosures are more visible and more difficult to prevent due to the open spatial configuration and intersections with many floor levels. Vinyl wallcoverings and similar materials can reduce debris and minimize the appearance of cracking, but may also conceal structural damage or breaches in the fire-resistance of the enclosure walls.

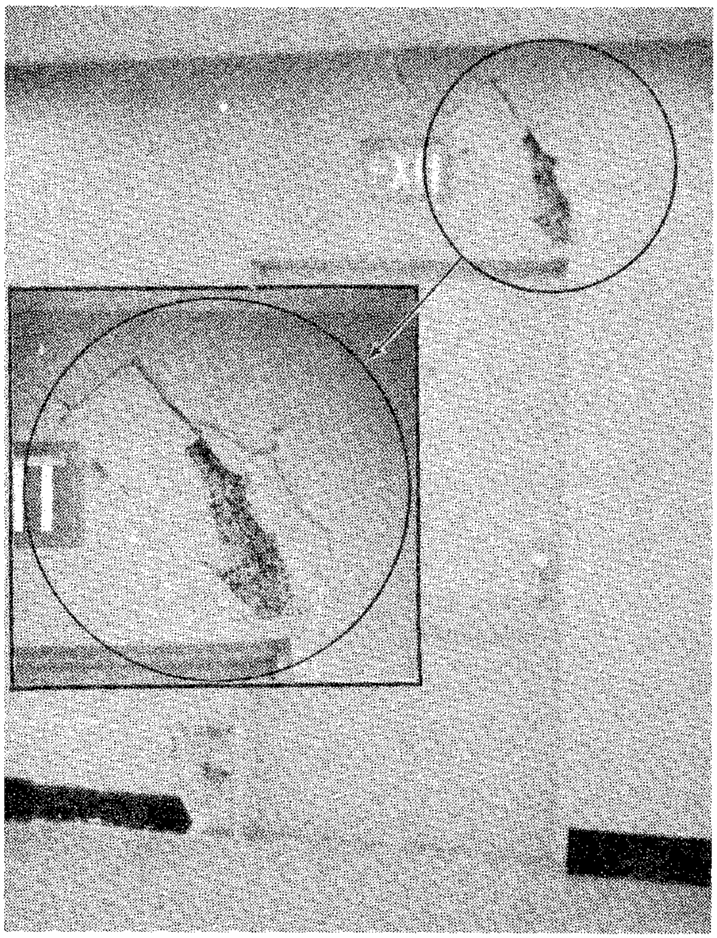


Fig. 4.4 Jammed stairwell door, Kaiser Foundation Hospital, 1971 San Fernando Earthquake. (Photo reproduced with permission from Engineering Aspects of the 1971 San Fernando Earthquake.)

4.4 Stairway Doors and Windows

Doors, windows and frames subjected to strong ground motions may be damaged by racking (see Fig. 2.9). Jammed exit doors and broken glass can seriously impair the use of stairways for emergency egress. Should fire occur, there exists the potential hazard of smoke infiltration through broken windows or jammed-open doors. Fire also compels the immediate evacuation of the building occupants via all available exits.

The design of special break-away doors or hinges has been suggested but not yet developed. Issues of building security would need to be considered as this area is studied. It may also be possible to devise fire-resistant door frames which could be mounted out of the plane of the wall in a manner that would resist deformations. In the meantime, one engineering firm in San Francisco keeps a crow-bar in their office for possible emergencies.

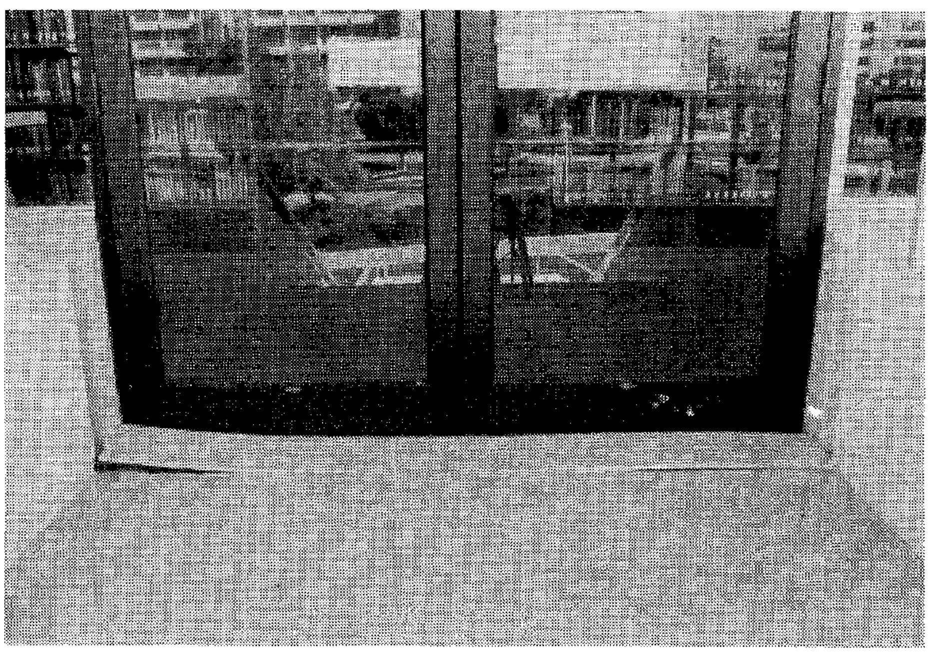


Fig. 4.5 Damaged seismic joint at door to exterior stairs, University of California Library, 1978 Santa Barbara Earthquake. (Photo courtesy of Richard K. Miller.)

4.5 Architectural, Mechanical and Electrical Components

The architect usually specifies the materials and installation of stairway components. Firm attachment of handrails and guardrails to adjacent walls and stair structure, and their strength to resist potential impact damage from falling debris, are important to the safe use of stairways following earthquake. The operations of normal service lighting, emergency lighting, ventilation systems, wet and dry standpipes for fire fighting, signs, and communications are particularly critical during life-threatening conditions.

Most code requirements for stairway component functioning relate to fire hazards with some stipulations for seismic forces. Equipment should be securely anchored or braced, with flexible connections for pipes and conduits, particularly when crossing seismic joints. Emergency lighting, provided by batteries or generators, must remain operational. Pendant light fixtures which could fall into exitways must be avoided. Incidental building services, such as ductwork or piping, should not interfere with the emergency egress functions of the stairways. Seismic joints and their covers should be located and detailed so as not to obstruct exit paths or doors. Positive attachment and connection details are being devised and published (see, for example, McGavin, 1981) specifically for earthquake resistance.

Fig. 4.6 Collapsed fire escape, Okamisawa Primary School, 1968 Tokachi-Oki Earthquake. (Photo reproduced with permission from General Report on the Tokachi-Oki Earthquake of 1968.)

4.6 Exterior Stairs

Fire escapes, usually made of steel, are attached to the outer walls of buildings to permit emergency egress from doors, balconies and windows. Although there has been little expressed concern for fire escapes, common on many older buildings, these stairs must be expected to be hazardous in earthquakes. Typically, they are attached to the building exteriors with connection details which may be susceptible to weathering and loss of strength through corrosion. Heavy counterweights on some fire escapes must be expected to aggravate their seismic risk.

> Fire escapes in older buildings may not have been recently examined. In the event of an earthquake, fire escapes may have to function as exits if stairs are blocked. Corroded anchorages or those embedded in damaged or deteriorated material may not provide lateral resistance specified by the code, and if so must be strengthened to comply. (ATC 3-06, 1978)

Monumental exterior stairs may suffer from ground movements and soil failures. Stiff exterior stairs can act as unintended braces if attached to the primary structure or as battering rams if separated only slightly. Tall exterior stair towers may tend to pound the adjacent building and to overturn. Attention must be paid to the locations of separation and seismic joints in the exit pathway (see Fig. 4.5).

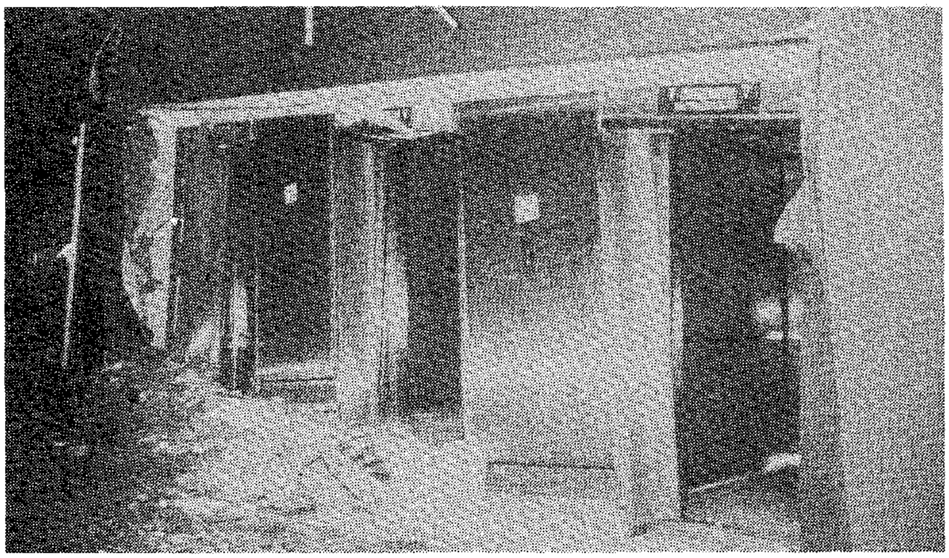


Fig. 4.7 Elevator and service stair lobby, Olive View Hospital, 1971 San Fernando Earthquake. Service stair doorway is visible at the extreme left (see also Fig. 1.1). (Photo reproduced with permission from Engineering Aspects of the 1971 San Fernando Earthquake.)

4.7 Elevators and Earthquakes

Stairways are the main focus of this report, as they must be expected to serve as the primary vertical links in a building's exit paths during a seismic emergency. Although elevators are the customary means of vertical circulation in many multi-story buildings, elevators have performed poorly in past earthquakes. Loss of power, equipment failures, counterweight derailment, damaged cables and cars, and jammed doors have rendered the elevators inoperable when most needed. Additionally, indiscriminate use of elevators during fires has caused many casualties. As a result most modern elevator systems have special emergency override controls to place the elevators out of normal service and under the command of the fire fighters.

In response to elevator damage and malfunctions in the 1971 San Fernando Earthquake, the State of California enacted regulations in 1975 to improve the safety of elevators in high-rise buildings. These include provision of seismic switch devices (to sense horizontal or vertical excitation of 0.15 g) and counterweight derailment devices (to detect displacement of counterweights from rails). Should either device be activated, the elevator would be programmed to travel slowly to the next floor and wait with open doors until it had been checked and returned to normal service or run by special key-operated emergency controls. Effectively, depending on the types of emergency devices and safety systems provided, elevators may not be available for evacuation of building occupants immediately following major earthquakes. The stairways remain the essential exit paths.

4.8 Concluding Remarks

Because stairways and exit paths are critical in fire and earthquake emergencies, they must receive careful attention in all phases of building design. Study of their performance in previous earthquakes reveals a wide range of potential hazards to access and egress. It may be necessary to develop performance standards for exits, to ensure the usability of these complex systems when needed.

Seismic design issues must be considered in the early stages of building project planning for earthquake zones. Some conceptual guidelines are available through the work of Arnold & Elsesser (1980), Arnold & Reitherman (1981), Dowrick (1977), Green (1978), McCue, Skaff & Boyce (1978), and in publications by the AIA Research Corporation. This body of knowledge, based on review of building failures and their relation to current design practice, should be verified experimentally and analytically, expanded, and more widely disseminated.

Collaboration of architect with structural engineer in preliminary design phases is advised. Basic configuration issues may be resolved and structural strategies developed for the location and number of stairway, elevator and service cores. Detection of "nonstructural" components which may (unintentionally) become part of the structural system may guide the reformulation of structural design strategies. Components which are protected by or isolated from the structural system could have standard construction details and provisions, which should be developed for the anticipated seismic forces.

The architect and engineer should discuss stairway isolation or integration strategies (considered in the next chapter of this report) and should consciously design for the selected strategy. This could reduce the likelihood of stairways acting as unintended structural elements. Problems caused by unfavorable interactions could then be minimized.

Detailing of stairway systems should be related to improved seismic performance. With increased understanding of stairway behavior, standard details and simplified means to predict behavior could be developed and made more readily available. These details should be reasonably easy and economical to construct and maintain.

Stairway enclosure walls must be designed and constructed to avoid brittle failures and debris hazards. Earthquake observations and some research work on wall assemblies can provide the basis for this study. Evaluation and testing of currently used wall materials, assemblies, and attachments of finish materials (particularly tiles, marble, and plaster) should be undertaken. Prefabricated components and systems such as gypsum shaft walls should be studied under seismic loadings.

The performance of doors and door frames has been problematic. The nature and amount of deformations imposed by wall movements should be reviewed, and improved installation methods should be developed. Break-away doors, special hinges, and techniques for frame mounting may be possible solutions.

Auxiliary equipment must be designed and installed for resistance to seismic accelerations and potential building deformations. Recent developments in mechanical and electrical system mountings and connections should be adapted to equipment found within the stairway system. Standard construction provisions and details should be collected, evaluated, and made specific to stairway conditions.

Research evaluations of stairway systems and system components should consider cost-benefits as well as life safety and seismic resistance. Studies should include initial costs, adverse effects of failure, and cost of repair (damageability).

5. STRUCTURAL DESIGN OF STAIRWAYS FOR EARTHQUAKES

On a building design project, the fundamental responsibility of the structural engineer is to analyze and design the primary structural system. By virtue of training and experience, the engineer may perform detailed code-based computations or dynamic analyses of the primary structure, with or without consideration of nonstructural interactions.

> One of the problems that faces the structural engineer is the introduction of supposedly nonstructural elements that affect the performance of the structure. The classic example is the stair that may act as a stiffening element for only a portion of the structure. (Steinbrugge, Manning & Degenkolb, 1967)

The structural engineer should take an active role in determining the extent of stairway-structure interaction by selecting an appropriate design strategy and by reviewing design proposals specifically to detect potential unintended structural interactions of stairway systems with the primary structural system. The stairway system should be detailed to effect the design strategy and, when possible, the adequacy of the design should be verified through analysis.

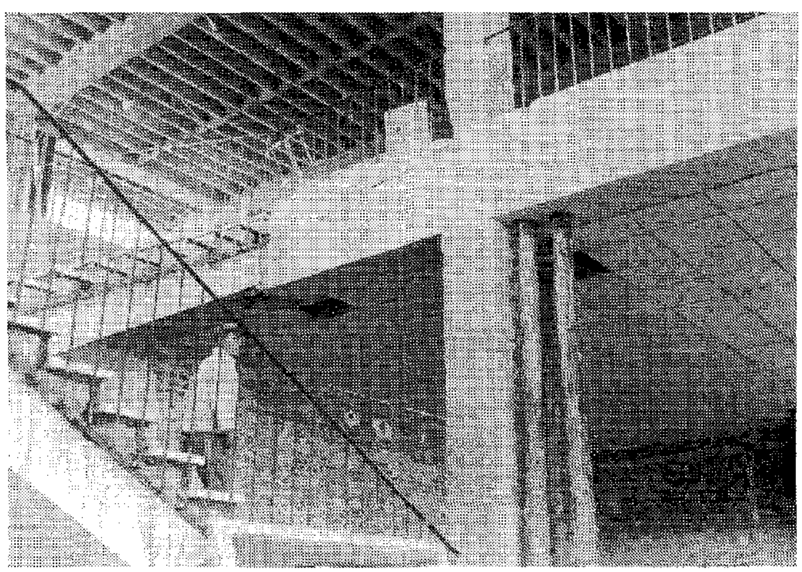


Fig. 5.1 Girder overstressed by stairway, Exhibition Building, 1963 Skopje Earthquake. (Photo courtesy of Mete A. Sozen)

5.1 The Design Team Role of the Structural Engineer

The structural engineer may either hold the prime design contract with the building owner/client, or serve as consultant to the architect or other design professional who acts as the general administrator of the project. In this latter case, the Structural Engineers Association of Northern California has prepared some guidelines for negotiating the contracted scope of work.

> The Basic Services responsibility of the structural engineer is limited to the analysis, design, detailing and specification of the Primary Structural System of the Building. The Primary Structural System is defined to mean that basic system which furnishes the required stiffness, strength and stability to support all structural and nonstructural elements and to resist within acceptable or codified limits the loads imposed upon the building by gravity, wind, earthquake....
>
> The Primary Structural System comprises the assembly of decking, slabs, joists, beams, girders, trusses, columns, cables, shells, vaults, domes, piers, walls and foundations, etc. necessary and sufficient for support. Non-structural elements are those architectural, mechanical, electrical and other components, for which specific design information must be furnished by the architect, by the mechanical, electrical, other consultants, and/or by the owner and which make no direct contribution to the Primary Structural System other than by imposing loads upon it. (Structural Engineers Association of Northern California, 1976)

Implicitly, the architect, electrical engineer, mechanical engineer, etc., are responsible for determining that intended nonstructural elements do not make "direct contribution," yet clearly the structural engineer is the design team professional who is most able to make this determination. In addition to the basic primary structural system services, the structural engineer may provide special services of analysis, design and detailing related to non-structural elements, including nonstructural partitions.

Although stairs are not specifically indicated in the "Guidelines for Scope and Compensation," the structural engineer is usually involved with the design and specification of stairway attachments, reinforcement, and strength characteristics. Standard office details may be used for typical service or emergency stairs, while the development of unique or monumental stairways may take up a disproportionate amount of engineering time and budget. Some standardized details are illustrated in structural engineering handbooks (see Fig. 1.2), but an accepted methodology for stairway design in seismic regions does not yet exist. There is a strong need for continuing dialogue among the members of the design team regarding building behavior characteristics, component and equipment needs, solid anchorage or flexible mounting techniques, damage limitations, and interaction concerns.

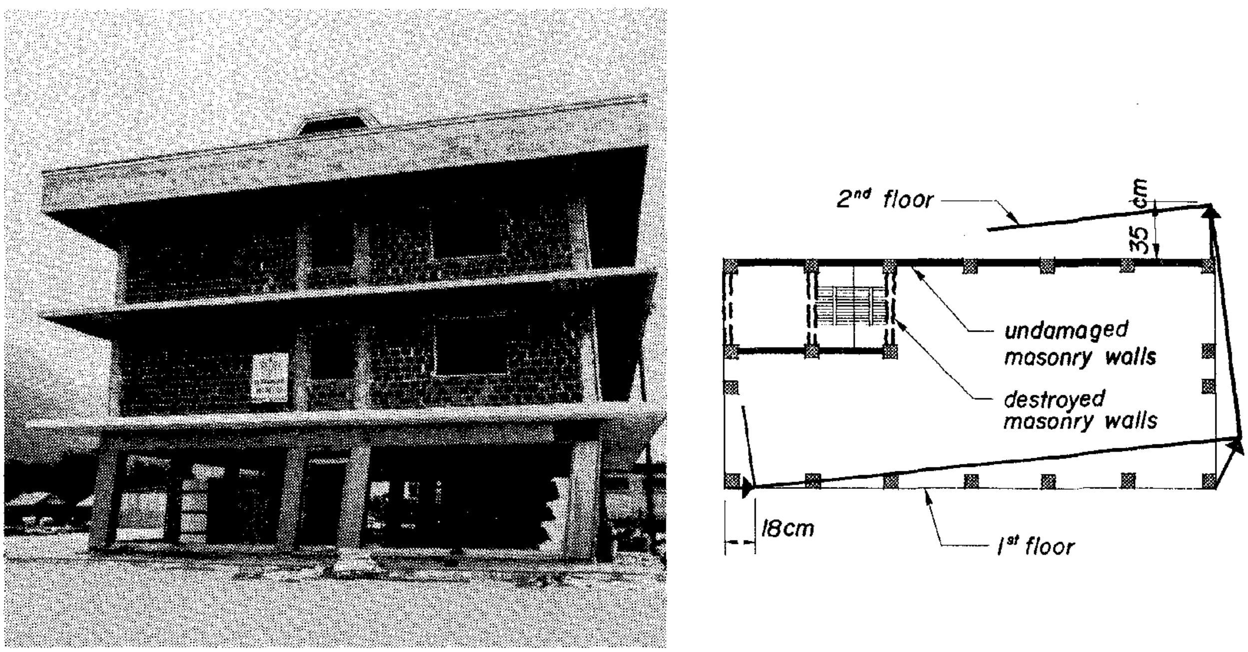


Fig. 5.2 Torsional damage around stairway, dwelling near Artegna, Italy, 1976 Friuli Earthquake. (Photo and diagram courtesy of Basler & Hofmann, Consulting Engineers, Zürich, Switzerland.)

5.2 Seismic Design Philosophies and Criteria

The stairway structural system is comprised of the stair flights and landings system, the stair enclosure system, and other components. All of these can be expected to experience seismic accelerations and must therefore be designed for the inertial forces associated with these accelerations. In addition, the primary structural system may interact with and impose deformations on the stairway structural system. The stair enclosure and stair flights may in turn interact with other stair components which they support.

Over the last several years, in response to nonstructural damage in severe earthquakes, several design philosophies related to this interaction problem have emerged.

> Nonstructural components must either be properly integrated with or effectively isolated from the basic structural system if excessive damage to the building and threat to life under earthquake induced movements are to be avoided. Some building components such as perimeter infill walls, cladding, internal partitions, non-bearing masonry walls, fire walls, stair framings, and other vertical shaftways, which under normal excitations are nonstructural, can become structurally very responsive in case of earthquake ground motions by interacting with the structure....The more flexible the basic structural system the worse the effects of nonstructural components will be. (Bertero, 1979)

One design philosophy, most strongly espoused by New Zealand engineers, emphasizes separation of nonstructural elements, including stairways, from the primary structural system of tall flexible buildings. By reducing interaction through carefully controlled connections or ductile isolators, damage and hazard are expected to be considerably lessened, although the separated systems will still experience accelerations. Another philosophy involves integration of the stairway and structural systems to take advantage of the stiffness characteristics of the stair enclosure walls. These stairway elements would then be designed as part of the primary structural system for seismic resistance.

Stairway systems may be designed as secondary structural components, yet integrated with the primary structural system if the primary system is stiff enough to protect the stairways from damaging deformations. However, integration of stairway systems which lack sufficient strength and stiffness to contribute usefully to the primary structure, with a flexible primary structure, may be expected to create local problems and potential hazards.

> Stairways may be considered as inclined extensions of horizontal diaphragms. Since the stairway has a vertical component it must be considered as a vertical shear wall and designed as such or be cut loose so as not to act in the case of earthquake shock. If the stiffness of the stairway acting as an inclined vertical shear wall is relatively small when compared to other vertical resisting elements in the building, the problem becomes less important. Thus, in general, the use of concrete stairs in a stiff building with masonry or concrete walls may be satisfactory. However, more flexible steel stairs should generally be used in buildings having a flexible moment-resisting frame. Interior stairs usually create a hole in the diaphragm which should be treated as an opening in the web of a plate girder. ("Tri-Services Manual," 1979)

> Concrete stairways often suffer seismic damage due to their inhibition of drift between connected floors. This can be avoided by providing a slip joint at the lower end of each stairway to eliminate the bracing effect of the stairway or by tying stairways to stairway shear walls. ("Tri-Services Manual," 1979)

Therefore, the stiffness contribution of the stairway systems should be considered since, although they may influence the overall structural behavior only slightly, they may cause significant local damage when seismically excited. This damage can be hazardous to the emergency egress functions of the stairways.

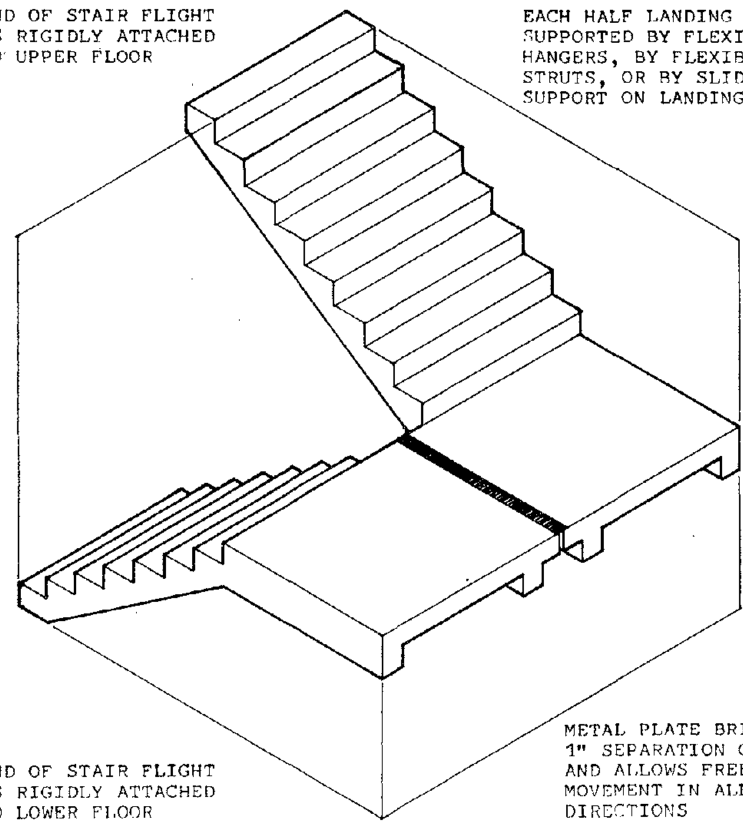


Fig. 5.3 Stair split at landing. (Conceptual diagram based on research published by O. A. Glogau, 1976 & 1977.)

5.3 Design Strategies for Stairway Isolation

Isolation of the stairway systems from the primary structural system is a conceptually attractive solution for seismic regions.

> The objective of the separation of non-structural components in buildings is to: (i) avoid damage in moderate earthquakes, (ii) minimize damage in severe earthquakes and thereby prevent possible panic or injury and loss of life to persons in and around buildings, (iii) prevent non-structural components from adversely altering the intended performance of the structure. (Glogau, 1976)

Stairways may be isolated from the primary structure in several ways, as completely separate exterior stair towers, as stair enclosure systems isolated from the surrounding building frame, or as stairways with sliding joints at the landings and enclosure walls. Separations may be achieved physically or mechanically by ductile and/or soft connections. The majority of research on stairway isolation has been undertaken in New Zealand, and is reported below.

> Separation of stairs can easily be achieved in a number of ways. A common method employed is to fix one end of each flight rigidly to a storey. The landing is split at the centre and either a sliding support is provided below or each flight and half landing is hung flexibly from above. Metal plates bridging the gap in the landing are fixed to one side only and free to move in all directions relative to the other. Care should be taken that separations are not crossed by rigid conduits for electrical services or fire detectors. (Glogau, 1977)

In Glogau's example, there is a 1-inch (2.5 cm) separation in the center of the intermediate landing slab (see Fig. 5.3).

> The support for the vertical load of the landing is arranged so that the landing is free to move laterally. Such support can be by flexible hangers, flexible struts or sliding support on a beam. (McKenzie, 1978)
>
> In the direction parallel to the landing the flights act as inclined diaphragms and although somewhat more flexible than along the flights freedom for movement in this direction should in general also be provided. (Glogau, 1976)

Another proposal for reducing the effects of story deformations calls for construction of independent stairways.

> One architecturally attractive solution is to design stairs as two flight or three flight free-standing staircases, spanning from the floor above to the floor below as a self contained structure, without any outside support to the landing. The flexibility for inter-storey movement at right angles to the main flights must be checked. (McKenzie, 1977)

The application of stairway isolation strategies, however, poses serious problems, particularly in regions where potentially destructive earthquake shaking occurs relatively frequently. Isolation demands a clear understanding of the seismic response of the building and stairways in order to estimate with sufficient accuracy the necessary separations. Too small separations, because of the effect of impact (pounding), can worsen the behavior rather than improve it. The selection of materials to close the gaps, and the detailing, construction, and maintenance to assure effective isolation during the service life of the building, are critical. These gaps in the enclosure walls may increase the potential for fire and smoke hazards in the stairway and may compromise acoustical isolation and thermal properties.

Another disadvantage of the isolation strategy is that it ignores the inherent large lateral stiffness of the stairs and their required enclosures, which can be used effectively to stiffen the whole building. One basic guideline in seismic resistant design and construction is that "if a mass has to be used, this mass should be used to improve the seismic resistant system of the building." Also,

> ...once seismic separations are provided movements tend to concentrate in these locations and take place in small earthquakes. (Glogau, 1976)

Separated stair towers require special attention to foundations to withstand the large overturning forces which may be expected.

Although much of the theoretical work on isolated stairways has been undertaken in New Zealand, in practice most new buildings constructed there utilize ductile shear wall systems which incorporate shear walls around the stairways.

Fig. 5.4 Collapsed structural stair cores, Four Seasons Apartment Building, 1964 Alaska Earthquake. (Ward W. Wells photograph, reproduced with permission from the American Iron and Steel Institute.)

5.4 Design Strategies for Stairway Integration

Many engineering offices which prefer to develop stiff primary structural systems also integrate the stairways into these systems for added stiffness, particularly in conjunction with shear walls and cores. In some cases, the stair enclosure walls are the designed primary structural system for lateral resistance. Stiffness contributions by the stair flights and landings (of reinforced concrete, for example) must be assumed but are usually not calculated, there being no easy method for this analysis.

> Stairwells and elevator cores are often among the most rigid elements of a structure, and therefore resist relatively large lateral forces. For this reason, severe damage is frequently found in and adjacent to them. Monolithic concrete stairs contribute substantially to the stiffness of the stairwells, and often are badly damaged. Steel stairs, being relatively flexible, encounter less damage. (Berg & Stratta, 1964)

> There are many nonstructural elements in buildings that tend to resist motion and do much work in the process. They are often quite beneficial and have saved many traditional-type buildings. Such elements include filler walls, stairways, and fireproofing. Although their damage may be very costly, these elements can save the structure. In modern design, the whole system should be integrated to minimize overall losses. A building with much aid from non-structural elements may have its basic frame stressed severely only after these elements have failed and the worst of the demand is over. In such a case, higher allowable stresses may be justified. However, situations like partial walls that cause overstress in the adjoining columns must be avoided. (Blume, 1977)

The existence of one or more stairway shafts can lead to significant changes in the overall dynamic characteristics of the building and, consequently, in its seismic response. The structural integration of stairways in a very flexible system (slender ductile moment-resistant space frame) can lead to a considerable increase in the stiffness of the structure. While this is definitely advantageous for controlling deformations and usually results in an increase in the overall lateral resistance to the system, it may lead to considerable increase in elastic strength and ductility demands. These two opposite effects have to be carefully evaluated. Stairway cores should be used in combination with service cores to provide the largest possible number of these cores in plan, distributed to avoid torsional effects. Single cores offer no redundancy and, if not properly designed and detailed, may result in a catastrophic failure.

In stairway integration strategies, the movement characteristics of the stairway structure and enclosure systems must be related to those of the primary structural system. Stairways in very stiff primary structures may be protected from damaging deformations. Stairways in ductile moment-resistant frame structures which are designed to stably dissipate seismic energy, may experience large deformations.

> In a flexible building such as a moment-resisting frame building, stairs are subject to severe distortion. Simple geometry demands it. The frame members can accommodate interstory lateral displacements almost entirely by flexural deformation accompanied by negligible axial deformation. Stairs subjected to the same interstory displacements must deform both flexurally and axially, or else the axial movement must be accompanied by some sort of slip joint between the stairs and the landings. The basic requirement is that a flexible building must have flexible stairs. (Berg & Degenkolb, 1973)

> Stairwells are often placed within the building core among the rigid elements. Rigid stair systems usually fail in nonrigid structures where shearing or racking in the floor system causes differential lateral movement between adjacent floors or lateral displacement. (Fisher, 1977)

Either deformations must be limited to those which can be accommodated by the stairway systems, or the stairways must be strengthened to withstand larger deformations. These deformations should be those which are expected in the actual building under real ground motions, not just those computed according to fictitious lateral seismic forces defined by building codes.

When rigid stairways and other service cores are structurally integrated with a flexible lateral structural system, considerable shear forces have to be transferred from the floor slabs to the enclosure walls. If this shear transfer has not been properly estimated and the needed collector bars supplied, large cracks can develop in the connection of the slab with the enclosure walls. Figure 2.2 illustrates this type of damage.

Stairways should be designed to ensure that the vertical and lateral load resisting abilities are not impaired and also to avoid any damage (structural or nonstructural) that would interfere with emergency exiting and rescue. In essence, stairways and exit routes should remain practically intact. If stairways are integrated into the primary structural system, the deformations of this system should be limited to tolerable distortions.

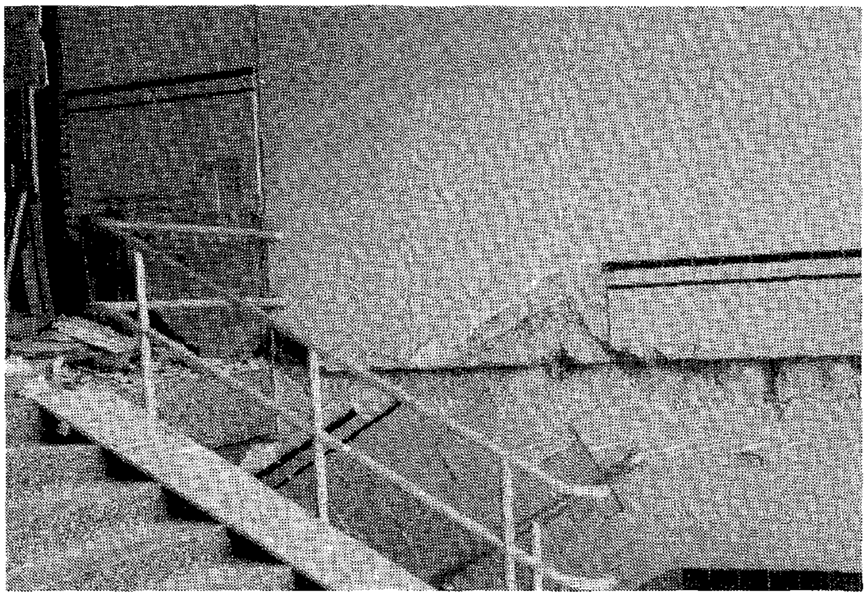


Fig. 5.5 Displacement at construction joint, Anchorage West High School, 1964 Alaska Earthquake. (Photo courtesy of the American Iron and Steel Institute.)

5.5 Structural Design of Stairway Enclosures

The design of stair enclosure walls as shear walls has received much attention from structural engineers. The Uniform Building Code and ATC 3-06 address the seismic force requirements for these walls. The relation of these enclosure walls to the primary structural system is beyond the scope of this report.

> A survey of various architectural layouts for high rise structural frames and shear walls has indicated that elevator shafts, stair wells or service wells, or other combination, can be employed as the structural component, i.e., the shear wall, without making any major changes, due to the structural requirements, in the original conceptual layout. (Kostem & Heckman, 1979)

The designer must pay attention to the locations of these enclosure walls, the connections of floor diaphragms to shear walls, the distribution of openings in these planes, and the means by which stair flights and landings are attached to the enclosure walls.

By virtue of their open spatial configuration, stairwells make visible construction defects exposed by severe earthquakes. A major nonstructural expense in building repair has been the patching and repainting of cracks in masonry, concrete, plaster, and gypsum dry wall stair enclosure walls.

> Construction joints apparently were not keyed and had not been sand blasted or slushed with grout: hence they formed planes of weakness along which failure could occur. This could be seen... in the Mt. McKinley building [in Anchorage] both in the exterior walls and in the stairwells. (Berg & Stratta, 1964)

One solution to such problems may be placing diagonal steel bars across major construction joints (especially those adjacent to stairways) to resist the total shear, or a reasonable portion thereof. Care must also be taken in the design of reinforcement around openings so that crushing or distortions will not jam essential exit doorways.

In keeping with the philosophy of stairway isolation, several New Zealand engineers have proposed schemes to isolate the stair enclosures from the primary structure.

> [Walls around stairs and lifts] are divided in their height... to form one rigid box fixed to the floor and one rigid box fixed to the slab above. Each box slides in any direction relative to the other. (Glogau, 1976)

Another proposal considers fire-resistive stair enclosure partitions in flexible framed buildings.

> One appropriate solution would be to construct these partitions as self supporting structures extending up from the foundation level and anchored laterally at selected floor levels so that they may deform and follow the movements in the primary structure. Deformation of the main structure would need to be limited to within the levels of strain which the constructional material of the wall can accommodate at the curvature induced by the geometry of the well walls in following the primary structure.
>
> Well walls mutually self supporting at each floor level can readily accommodate movement; but there are problems of fire and smoke stopping at the head and there can be interaction problems at junctions with ceilings supported from the slab above...
>
> Provisions need to be made for access for repair to restore the fire protection requirements of such partitions. (Allardice, 1977)

Many modern high-rise buildings of flexible primary structure contain flexible (steel) stairs enclosed for fire resistance in gypsum shaft wall systems. These lightweight nonbearing assemblies consist of steel studs and two or more layers of gypsum panels. Cracking at joints and some spalling of finish materials may be expected in severe earthquakes if the assembly can not accommodate the deformations of the flexible structural system.

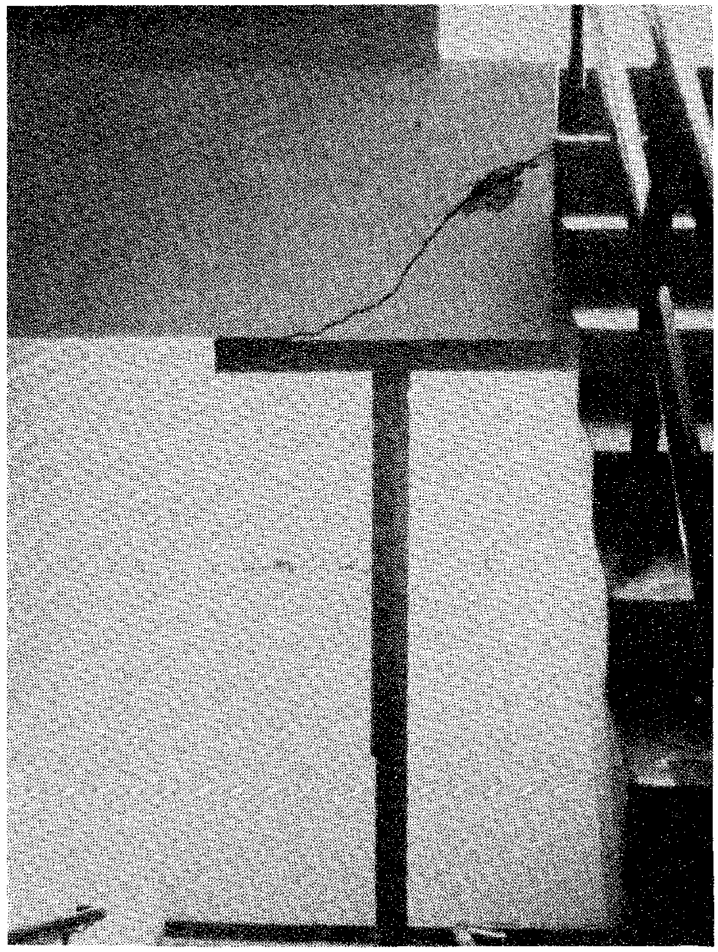


Fig. 5.6 Stair landing damage, Pacoima Lutheran Hospital, 1971 San Fernando Earthquake. (See Fig. 2.8) (Photo reproduced with permission from Engineering Aspects of the 1971 San Fernando Earthquake.)

5.6 Structural Analysis of Stairways

Among structural engineers there appears to be a concensus that,

> Consideration must be given in the design of the lateral load resisting system of the stiffening effects of elements not considered as part of the system, such as floor slabs, stairs, nonstructural infill walls, etc. (Council on Tall Buildings, Group CL, 1980)

> The behavior of a structure is influenced by the presence of nonstructural components, and the designer must consider how the total structure will respond to the actual ground movement, not just how the ideal structure would react under an idealized seismic force. (Berg, 1964)

Ideally the designer should have analytical tools to estimate the behavior of proposed stairways within a predicted response of the "total structure" so that the stairways may be designed accordingly. Yet presently,

> · Staircase ramps afford one of the most critical examples of a structural solution met in everyday practice for which there is still no satisfactory method of analysis... (Newmark & Rosenblueth, 1971),

for lateral load response. And,

> For the most part the available [general-purpose computer] programs disregard the effect of nonstructural elements, because few, if any, realistic idealizations (mathematical models) of the nonlinear behavior of common nonstructural elements have been formulated. (Bertero, 1979)

For gravity load analysis a stairway is typically taken to be an independent system supported by the primary structural system in either a simple or a fixed manner. A single-flight stair, with or without landings, is normally analyzed as if it is a simple beam, considering only flexural stresses, although Liebenberg (1960) presented a means to take account of the combined effects of flexural stresses and axial stresses for single-flight stairs with landings by modeling the stairs as an equivalent pinned assembly of beam elements. Liebenberg applied this same approach to the more difficult task of the gravity load analysis of a free-standing stairway, a stairway with one or more unsupported intermediate landings (sometimes referred to as either a cantilevered stairway or free flight stairway). Earlier, Fuchssteiner (1954) suggested another approach to the gravity load analysis of free-standing stairways wherein the stairs are modeled as an equivalent assembly of rigidly connected beam elements (i.e., a space frame). These two studies initiated two decades of research of the gravity load analysis of free-standing and helicoidal stairways (see also Siev, 1962; Gould, 1963; Taleb, 1964; Cusens & Kuang, 1965 & 1966; Cusens, 1966; Chandrashekhara & Srinivasan, 1972; Rajagopalan, 1973; Rutenberg, 1975; Ng & Chetty, 1975).

The results of these research efforts suggest that for lateral load analysis the initial elastic contribution of typical stairways to the behavior of the "total structure" may be approximately modeled by an equivalent assembly of rigidly connected beam elements following Fuchssteiner's approach. Section and material properties for the beams of such an assembly may be based upon actual as-built geometry and materials of the stairs ignoring the steps. "Sawtooth" or "slabless" stairs, constructed so that the underside of the stair is parallel to the risers and treads, may require a different approach. For reinforced concrete stairs, uncertainties introduced by cracking and by the presence of construction joints limit the accuracy of any attempt to model the initial elastic behavior of the stair/structure total system.

These suggestions are, of course, speculative at this time and will require further investigation, but even if such an equivalent space frame approach provides sufficient accuracy, many stair/structure total systems would have to be modeled as complete three-dimensional assemblies to correctly model the stair/structure interaction. Furthermore, openings in floors due to the presence of stairs and the influence of stair enclosure walls will tend to add more complications to the modeling effort. For many situations the effort required to develop a complete three-dimensional model of the total structure may be difficult to justify. For example, a complete three-dimensional framework model using the equivalent beam elements suggested above may be expected to capture the global and local response behavior yet may not capture important local details of elastic behavior (e.g., stress concentration) that result from the detailed geometry of the stairs, stair enclosures, openings in floor slabs, and stair support.

The initial elastic detailed local behavior of a stairway system may be modeled using plate finite element analysis (Smith, 1980). Such a detailed finite element modeling of stairway systems within a "total" system offers an available, albeit cost prohibitive, approach. Research published by Sandberg and Beaufait (1980) of studies of a shear wall stair shaft comparing elastic finite element analysis, elastic beam theory, and model studies, showed general agreement. They worked with an idealized six-story stair and enclosure system, with and without stair flights (attached only to landings, not to the side walls), and tested 1/24 scale plexiglas models to obtain their data. They stated that "the contribution of the stairways to the overall stiffness of the shear wall-stair shaft is negligible" for their system, in which the stair flights were not directly attached to the shear walls. Yet they also suggested that,

> Stair system stresses resulting from lateral loading of the shear wall-stair shaft were shown to be high. To overcome this problem, it is suggested that the stair system be isolated from the surrounding shear wall. This would allow the stair system to "float" within the shaft. (Sandberg & Beaufait, 1980)

In the inelastic range, very different conclusions could be drawn.

The problem of modeling stair systems may be expected to be complicated by the complexities of (often nonlinear) response mechanisms in the variety of stairway-structure combinations. Several of these analytical issues have been raised.

> To further complicate the problem of modeling, the relative contribution of structural, nonstructural, and foundation stiffness to the total model varies with the level of motion (e.g., distortion) produced by the earthquake....Under large amplitude motions produced by a major earthquake, the accidental ties between structural and nonstructural elements may be partially or totally broken or the nonstructural elements may become damaged resulting in a loss of stiffness contributed by these elements. (Gates, 1978)

> The question of shear lag and effective flange width is ... applicable to shear walls that intersect in a common corner. Typical examples are elevator and stair towers where all the walls are integrally tied together by the lacing action of the stairs and floor diaphragms. Much judgment must be exercised by the engineer in these cases....In certain instances the truss-like action of the stair risers is included in the stiffness calculation. (Gates, 1978)

> A shear wall stair shaft, with door openings and a stairway, will experience a torsional displacement even when subjected to a lateral disturbance because of the fact that it has no unique shear center. This will have an influence on the lateral response of any building structure of which it is a part. (Sandberg & Beaufait, 1980)

Experimental studies will most certainly add other nonlinear complications to the problem of analytically modeling the most common stairway systems. Yet simple methods of analysis are needed, as complex studies may not be justified economically.

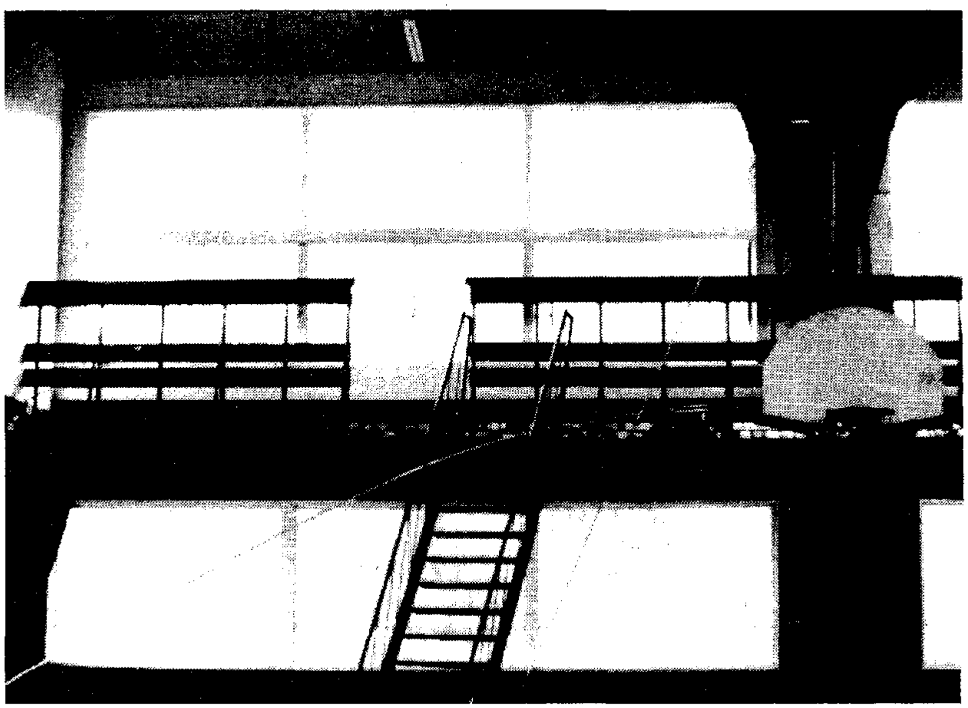


Fig. 5.7 Displaced gallery stair, Shichihyaku Primary School Gymnasium, 1968 Tokachi-Oki Earthquake. (Photo reproduced with permission from General Report on the Tokachi-Oki Earthquake of 1968.)

5.7 Stairway Connections and Detailing

Stairway detailing is generally a matter of office practice, as very few handbooks provided tested schemes for connections, reinforcement, or member sizing to ensure ductility and strength in seismic conditions. The design strategies of isolation and integration, and their implications for drift and distortion, must be carried through in stairway details and construction.

Failed materials or connections can have catastrophic effects on the emergency functioning of the stairways and exits.

In addition to providing some details of reinforced concrete stair sections (see Fig. 1.3), Dowrick states,

> If stairs are part of a horizontal diaphragm or moment resisting framework they should be reinforced accordingly. Due care must then be taken at the changes in slope to confine the longitudinal bars. (Dowrick, 1977)

Commentary in the New Zealand Code of Practice regarding separation of rigid brittle exterior claddings whose failure may create hazards, states,

> Inserts in concrete should be attached to or hooked around reinforcing steel, or otherwise terminated to effectively transfer seismic forces. Required anchors in masonry walls of hollow units or cavity walls should enter a reinforced grouted structural element of the wall. (NZS 4203 : 1976, Commentary)

This has implications for the attachment of steel stair structural systems to their enclosures.

In designing the connections it is important to estimate accurately the amount of deformation they must sustain.

> Expansion joints, flashings, partitions, and stairwells should be designed for seismic movements. The amount of movement to be designed into these elements should be based upon maximum possible interstory drifts, rather than upon deflections computed for code seismic forces (unless code seismic forces are increased considerably). (Blume, 1973a)

Welded or bolted connections supporting stair landings and flights must withstand these maximum drifts to prevent serious reduction in load-carrying capacity (as has occurred in previous earthquakes) or complete loss of the stairs. Stair landing connections to adjacent structural columns (see Fig. 1.2) need careful consideration so that significant damage (see Fig. 2.1, Fig. 2.3, and Fig. 6.1) can be avoided.

5.8 Concluding Remarks

Determining the influence of stairway systems upon the behavior of the primary structure is a task for the structural engineer. There is a need for evaluating stairway contributions in terms of both overall and local responses of the structure. Although nonstructural elements have been defined as making "no direct contribution" except by imposing inertial loads, complete assurance that a stairway will not become an unintentional structural element requires structural engineering review of the stairway design. Analytical tools for this evaluation are not readily available and need to be established.

Design strategies for stairways must be related to the dynamic nature of the primary structural system in which they are contained. Stiff primary structural systems allow stairway integration strategies. Flexible primary structural systems would seem to require either isolation of stiff stairways or integration of flexible stair enclosures and stair flights. If stair enclosures are developed as part of the primary structural system, other components of the stairway should receive greater attention to reduce potential hazards and damage. In all strategies the components must be designed to resist inertial loads generated by their own mass.

Separation strategies avoid some problems of interaction, but in doing so introduce new structural problems of support, construction, and isolation details. Separations require careful consideration of materials, weatherproofing, fire and smoke infiltration, acoustics, and maintenance. Research would be necessary to determine the interstory drift appropriate for detailing different building structural types. Because the inclusion of structurally separate stairways within buildings is a relatively new concept, it requires study to better understand behavior and thereby to improve design methods and construction techniques.

Rational design procedures are best based upon methods of analysis to predict the response of stairway systems to expected ground motions. The reliability of these analytical methods must be demonstrated experimentally, and the cost of analysis must be kept within certain economic limits. Even if such methods are developed one must expect that structural engineers will still need to use judgment in deciding which stairway configurations warrant costly analytical study. Although some unanticipated unintentionally structural stairways may be overlooked, the development of new methods of analysis will increase understanding and aid judgment regarding stairway response.

In as much as different design philosophies exist and methods of analysis are practically not available, standard details should be developed for the various stairway design strategies and compiled in an accessible reference. These should include provisions for maintenance, fire separation, and repair. Should stairway structural problems prove too "untidy" in analysis, standardized design provisions (such as prescriptive rather than performance code requirements) may become essential.

6. STAIRWAYS IN EXISTING BUILDINGS

The very large numbers of existing buildings in seismically active regions increase the possibility of safety hazards from stairway damage. Most of these buildings were constructed under older earthquake design codes, if any, with few requirements for emergency egress routes. The range of damage presented in Chapter 2 of this report illustrates the vulnerability of these older stairways, particularly to the failure of brittle enclosure walls and to unanticipated structural interactions.

Seismic performance may be improved through maintenance of unobstructed exitways and through remodeling or retrofitting of stairway systems. Stairway rehabilitation could take place when the building is renovated to current code standards, although historic buildings raise special problems since they may not easily accommodate such alterations. Legislation for retroactive compliance is very difficult to enact and enforce, and may not be expected realistically (although the recently adopted Los Angeles code provisions for strengthening unreinforced masonry buildings are a notable example). However, stairways in buildings of emergency function, public assembly, or special importance must receive attention to reduce life hazards associated with stairway damage.

6.1 Stairway Maintenance

Adequate maintenance of exitway systems will help assure their emergency operation. Building managers should periodically check that exits are free of obstructions and debris, that doors are kept unlocked in the direction of travel, that emergency lighting, ventilating and communication systems are functional, and that sufficiently informative signs are displayed. Particular attention must be paid to maintaining seismic joints and isolation devices so they may perform as intended.

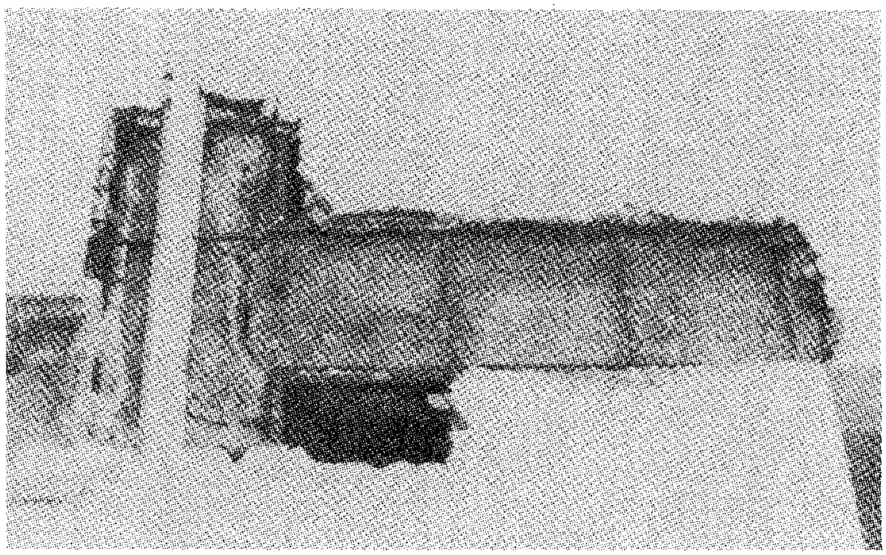


Fig. 6.1 Intermediate stair landing damage at beam-column joint, Holiday Inn on Marengo St., 1971 San Fernando Earthquake. (GAB Business Services, Inc. photograph, reproduced with permission from San Fernando, California, Earthquake of February 9, 1971.)

6.2 Stairway Rehabilitation

Seismic safety evaluation methodologies for existing buildings must include procedures for identifying hazardous stairway conditions and techniques for mitigating these hazards. Preliminary screening could determine which buildings most critically need closer study. Hazard identification could be based on field investigations and checklists, materials testing, analytical model techniques, or criteria for performance, drift limits, and separation limits. Hazard reduction techniques include stairway rehabilitation by retrofit or reconstruction to new standards, by demolition or abandonment of dangerous stairs, or by changing the building use or occupancy to lower the performance criteria.

Building repair and renovation, before or after an earthquake, provide the opportunity to review the potential safety of the emergency exit paths and stairways. Notoriously hazardous conditions such as brittle unreinforced enclosure walls or rigid stairways bracing primary structural elements could be improved.

> Fire escapes should be load tested where practical. If such a procedure is impractical on a large scale, a detailed visual inspection should be made to identify defects requiring correction. (ATC 3-06, 1978)

Loss of fire resistive characteristics, for example, large cracks developed in masonry enclosures by the building's motions in windstorms and earthquakes, must be corrected.

Scattered throughout the literature are references to proposed and performed repair or retrofit techniques. These include replacement of overstressed steel and spalled concrete, in accordance with accepted procedures. Crack repairs in concrete walls may also involve restoration of the required fire resistance; the structure may be weaker than originally designed, with uncertain strength and stiffness. Unreinforced masonry and tile block walls have failed in many earthquakes and may also be damaged by heat of fire.

> Most of the casualties caused by shattered panels are due to masonry falling from the external walls and from the walls around stairways. Hence steps should be taken to prevent falling masonry. A wire mesh may be placed outside the panels and attached to the building frame. This would then be covered by plaster. A similar wire mesh should be used to prevent masonry falling down stairways. (Skinner, 1968)

Compilation and dissemination of information on improving the seismic performance of existing stairways and on repairing earthquake damage will improve the life safety aspects of buildings. Presently there is little research on repairs, and those performed are considered on a case-by-case basis. A methodology must be developed for conducting the repairs, beginning with evaluation of the cause of damage, the soundness of the present construction, and the need to retrofit the existing stairways, before repairing the damage observed. Repair methodologies for various types of stairs could be compiled and integrated with analytical studies and testing.

6.3 Emergency Preparedness and Stairways

Familiarization of building occupants with the seismic provisions of their particular building can help reduce casualties in the event of a damaging earthquake. This includes a basic understanding of the anticipated building motions, the existence of hazardous materials or conditions, and the expected performance of the stairway systems.

Locations of all stairways should be known (and indicated by signs and/or diagrams) in the event that the nearest exit is jammed or unusable. Techniques for releasing jammed doors and the locations of pry bars should be indicated, and doors which are locked from the stairwell side for security reasons should be identified. (Alternatively, unlocked doors at least every five stories should be marked.) Occupants should be informed of hazards associated with enclosure wall failures and should be discouraged from entering stairways until the building motions have stopped (unless the particular situation indicates that stairways are safer than the main building). Occupants should know that some cracking of plaster or gypsum walls can be expected and is not usually indicative of serious structural failure.

People in stairways must proceed with extreme caution. Damaged stairs may have reduced width and/or load-carrying capacity. Debris on treads may cause tripping or may be kicked down on people below. People may stop on the stairway for various reasons, and rescue workers may be coming up the stairs as well.

Special consideration must be given to the evacuation of people who can not walk down long stairways due to age, poor health or physical disability. Wheelchairs may need to be abandoned and their owners carried down the stairs. Many stairways are not wide enough to accommodate stretchers at the landing turns. Injured and disabled people should have priority in the elevators, if functioning.

Occupants should be familiar with the building's emergency communications systems and the locations and use of wet standpipes and fire extinguishers. Information about expected elevator operations following earthquakes should be given, including the types of seismic detection devices (many elevators, if undamaged, will be operable) and when elevator use is appropriate.

Depending on the severity of the earthquake and its effects, fire fighters and rescue workers may be involved at other locations. Building occupants must be able to take care of themselves during the first several hours.

7. GENERAL CONCLUSIONS, RECOMMENDATIONS, AND RESEARCH NEEDS

From the reviews and studies of stairway design, analysis and performance discussed in this report, several major observations can be made.

7.1 General Conclusions

(a) Because stairways are the primary vertical emergency exit routes in multi-story buildings, they must be designed so that their use for safe egress and access during and after an earthquake can be assured. Functional stairways are especially critical should fire occur, since there would be more imperative conditions under which to evacuate the building. Elevators may be unserviceable after moderate or strong seismic shaking, and they are not code-recognized exits.

(b) Jammed doors, debris-littered treads, detached components, and darkness are the most common effects of stairway response to seismic shaking. As they can seriously interfere with emergency functions, they should be avoided or minimized.

(c) Most of the earthquake damage is due to interactions of stairway structural systems with their nonstructural components and particularly with the primary structural system of the building.

(d) It has been shown that stair flights and enclosure walls have influenced, usually unintentionally, the dynamic characteristics and seismic responses of primary structures. Lack of awareness of and attention to this problem have contributed to local structural damage and sometimes to structural collapse.

(e) Since stairways are often very complex systems integrating a variety of architectural, structural, electrical, and mechanical components, their seismic behavior may be expected to involve complex interactions among these components. The important three-dimensional character of stairway behavior and influence further complicates the seismic response.

(f) At present there exist no practical general analytical methods for predicting even the simplest aspects of stairway dynamic interaction with the primary structure, and there is little consensus on design strategies for the stairway/structure relationship. Few details for structural connections and assemblies to withstand strong seismic shaking have been tested.

(g) Present U.S. seismic codes do not provide guidelines regarding the proper selection of stairway systems, their design, or their construction. Only a few foreign codes specifically mention the earthquake resistant design of stairways.

(h) Current design practice relies upon past designs and published recommendations that have been developed without addressing seismic issues in a comprehensive or detailed manner. Yet the required high level of performance of stairways as exits makes their seismic design an important life safety concern.

7.2 Recommendations for Immediate Improvement of Stairway Design

(a) Acquiring a better understanding of stairway damage mechanisms requires more detailed information about and analysis of problems occuring in moderate and strong earthquake shaking. Reconnaissance and investigating teams should note stairway conditions, materials and construction, adjacent structural damage due to possible interaction, possible damage mechanisms, and interference with evacuation. Post-earthquake studies should include investigations of human reactions and behavior.

(b) Architectural design of buildings would benefit from the consolidation of planning concepts for building configurations and stairway locations. Seismic implications of various architectural and structural schemes should be studied and published so that designers may either avoid or consciously accommodate situations that have been problematic in the past. Cost-benefit analyses of different design options should be considered in relation to seismic resistance, life safety, and property damage.

(c) The structural engineer in collaboration with the architect must consider the effects of stairway systems at the early stages of building design so that an appropriate strategy may be selected and applied. Presently, specific recommendations for analysis and detailing of stairways for seismic motions are scarce and scattered throughout the professional literature. Reference materials should be upgraded to include seismic implications of standard details.

(d) Seismic codes should include guidelines and comments about the problem of interactions between stairways and the primary structural system. Building code officials should review the provisions of their regulations concerning the performance of exits in earthquakes as well as in fires. The tentative model code outlined in this report may be used as a basis for more specific and detailed requirements. Omissions and ambiguities should be reduced so that designers using the code provisions could demonstrate the acceptability of their egress schemes for earthquake hazards.

(e) Building officials should conduct thorough reviews of the design calculations and drawings to assure that proper design of stairways has been accomplished and thorough inspections to verify that such design is achieved in the field.

(f) Development and dissemination of improved analytical methods will enable structural engineers to predict more closely the stairway system response. This response may be accommodated through proper selection of materials, design and detailing, as well as through proper design and detailing of stairway connections with the primary structural system.

(g) Information about the anticipated stairway response must be communicated by the structural engineer to the architect, electrical engineer, mechanical engineer, and other consultants so that attachments, bracings, material assemblies, and equipment characteristics may be designed for the expected displacements and accelerations. These professionals should review the expected seismic performance of the total exit and stairway systems to reduce potential interaction damage and disruptions in emergency functioning.

(h) The concepts by which the stairways are designed must be communicated to the building owner, the occupants, and the maintenance staff so that expected behavior during major earthquakes may be anticipated, and particular details or devices (such as separation joints) may be maintained as intended. Better understanding of the building's emergency systems and expected seismic response will aid the development of more comprehensive disaster response plans for the building occupants.

(i) Existing buildings should be surveyed so that hazardous conditions in the exit pathways can be removed or improved. This is appropriate when all or part of the building is undergoing renovation or rehabilitation, but is especially important for any building having critical emergency functions, places of public assembly, high numbers of occupants, or hazardous contents.

7.3 Research Needs

Research needs are concerned with improving the design and construction of stairways in new buildings and the repair and/or retrofit of stairways in existing buildings.

(a) It is recommended that a coordinated research program integrating literature and field surveys with analytical and experimental studies be developed. This research program should first identify the different stairway systems that show promising features for adequate fire and seismic performance, and then initiate the needed

(1) experimental studies to improve the understanding of behavior of stairway system components and assemblies, and the interaction of the most promising, specific stairway systems with primary structural systems,

(2) experimental studies to develop improved methods and details of construction, with

(3) matching analytical studies to develop rational mathematical idealizations of components and system behavior to serve research and development efforts, and,

(4) matching studies to develop simplified analysis and design procedures to enable the professional designer to predict the behavior of the design choices and to design accordingly.

The knowledge gained from this research program could lead to the development of new stairway systems as optimal solutions for each particular building structural system. However, to identify the different stairway systems that show promising features, it is necessary to conduct the following studies:

(b) Ideally, experimental studies of the load-deformation behavior, carried on into the inelastic range with load reversal, of typical stairway structural and enclosure components should be undertaken to develop analytical models that will serve as a basis for understanding the real stairway system behavior. An experimental program of this nature could be impractically ambitious as the number and variety of even typical components is great. Therefore, it may only be reasonable to attempt to investigate analytically the sensitivity of the seismic response of the system to variations of most of the main parameters (components) by modeling the behavior of these components using available structural idealizations.

(c) Analytical studies should be undertaken to see if the initial elastic response behavior of stairway structural systems alone and interacting with primary structural systems can be accurately modeled using available analytical techniques correlating predicted behavior with measured behavior. The use of plate finite elements, beam elements, or a constraint approach (similar to that used by Axley and Bertero (1979) for the analysis of infill frames) might be considered. These studies should seek to develop methods of analysis, using existing techniques, to model not only the behavior of the isolated stairway system but also the complete three-dimensional behavior of the combined stairway system/primary structural system as well as the detailed local behavior of stairway system's attachments to the primary system.

(d) Inasmuch as such elastic modeling techniques are likely to be of most use to the designer of stairway systems, these analytical studies should seek to develop simplified methods of analysis that may be implemented with available computer programs and to produce design criteria (e.g., limit states for corresponding load conditions) for their application to practical problems of design.

(e) Analytical studies should also be undertaken to see if aspects of the nonlinear elastic and particularly nonlinear inelastic response behavior of stairway structural systems may be modeled with existing techniques. It is reasonable to initiate these studies after some experience with elastic modeling has been gained. In the very near future, nonlinear idealizations most likely will be of greatest use to the researcher, rather than to the professional designer. Efforts should be devoted to use the research results based on nonlinear response studies to develop simplified practical methods that utilize linear elastic analysis techniques.

(f) Because building stairway construction involves many nonstructural components which have suffered significant damage in past earthquakes, the development of simplified methods for the analysis and design of these components has become a pressing problem in recent years. While many nonstructural components can be reliably designed at this time (e.g., the lighter and smaller nonstructural components attached to stiffer structural components, such as handrails, light fixtures, and signs), other nonstructural components, such as doorways and standpipes, may prove more difficult. Analytical studies should be undertaken to develop simplified methods of analysis and design for these hazardous and problematic nonstructural components.

(g) Most recently, the need to strengthen, demolish or modify the use of existing hazardous buildings to reduce life safety hazards has been recognized as an important national problem. Research efforts have been initiated to answer this need. Some of these efforts are directed toward developing analytical methods to predict the behavior of existing buildings. Researchers in this area should be encouraged to include considerations of stairway systems in their efforts.

Finally, the main features and conclusions of research on the seismic performance of stairways should be compiled and made accessible to design professionals. Design guidelines, strategy considerations, simple analytical methods, improved details, new construction techniques, and performance standards may reduce the amount of stairway damage encountered in future earthquakes and mitigate these hazards to human life.

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