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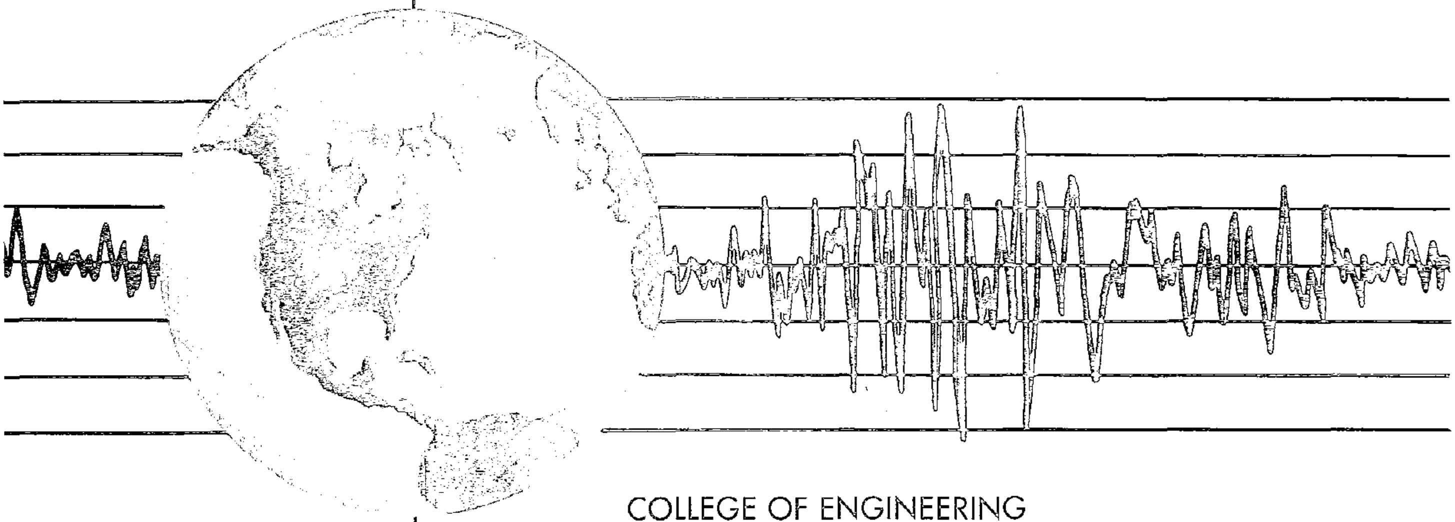
EARTHQUAKE ENGINEERING RESEARCH CENTER

SLOTTED BOLTED CONNECTION ENERGY DISSIPATORS

by

CARL E. GRIGORIAN
TSONG-SHUOH YANG
EGOR P. POPOV

Report to the National Science Foundation



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Slotted Bolted Connections (SBCs) are modified bolted connections designed to dissipate energy through friction during rectilinear tension and compression loading cycles. Experimental results on two types of SBCs are reported. In one type, friction occurs between clean mill scale steel surfaces; in the other, friction is between clean mill scale steel and brass surfaces. The behavior of connections with brass on steel frictional surfaces is found to be more uniform and simpler to model analytically than that with steel on steel surfaces. These connections maintain essentially constant slip force, and unlike those with steel on steel surfaces, require minimal overstrength of the system in design. The frictional mechanisms giving rise to the observed behavior are explained. As an example of application a one story diagonally braced frame was designed and its behavior determined for four different earthquakes. Experimental results are presented for the fabricated SBC for this frame subjected consecutively to the four displacment histories derived from these earthquakes. The agreement between the analytical and experimental results is found to be excellent. Because of the intrinsic simplicity of the SBCs and their very low cost, their use in seismic design and retrofit applications appears to be very promising.

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Abstract

Slotted Bolted Connections (SBCs) are modified bolted connections designed to dissipate energy through friction during rectilinear tension and compression loading cycles. Experimental results on two types of SBCs are reported. In one type, friction occurs between clean mill scale steel surfaces; in the other, friction is between clean mill scale steel and brass surfaces. The behavior of connections with brass on steel frictional surfaces is found to be more uniform and simpler to model analytically than that with steel on steel surfaces. These connections maintain essentially constant slip force, and unlike those with steel on steel surfaces, require minimal overstrength of the system in design. The frictional mechanisms giving rise to the observed behavior are explained. As an example of application a one story diagonally braced frame was designed and its behavior determined for four different earthquakes. Experimental results are presented for the fabricated SBC for this frame subjected consecutively to the four displacement histories derived from these earthquakes. The agreement between the analytical and experimental results is found to be excellent. Because of the intrinsic simplicity of the SBCs and their very low cost, their use in seismic design and retrofit applications appears to be very promising.

Introductory Remarks

This report was prepared for publication in a theme issue of **Earthquake Spectra** dealing with energy dissipation systems for earthquake hazard mitigation. The results described in this paper matured after several years of work.

An Advisory Committee on **Slotted Bolted Connections** (SBCs) for energy dissipation under cyclic load consisting of A.L. Collins, L.H. Daniels, T.F. Fitzgerald, L.A. Napper, F.R. Preece, H.J. Sexton and T.C. Zsutty was most encouraging in this research effort.

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Introduction

Various types of energy dissipating devices, utilizing friction as means of energy dissipation, have been tested and studied by researchers [4, 6, 7]. Two of the common features of these devices have been that their manufacture requires precision work or exotic materials and that their installation demands specialized training. Consequently, the additional expense in using such devices has prevented their wide acceptance in engineering practice. The development of the Slotted Bolted Connections (SBCs) as energy dissipators represents an attempt to overcome the abovementioned shortcomings of these systems. SBCs, as presented in this paper, require only slight modification of standard construction practice, and require materials that are widely available commercially.

In this paper a Slotted Bolted Connection (SBC), see Figure 1, refers to a bolted connection where the elongated holes or slots in the main connecting plate, in which the bolts are seated, are parallel to the line of loading. In addition a Belleville washer [8] is placed under the nut. Two types of SBC specimen are discussed in this paper, one with brass insert plates and one without. Upon tightening of the bolts, the main plate is "sandwiched" directly between either the brass insert plates or the outer steel plates. The holes in the brass insert plates and in the steel outer plates are of standard size. When the tensile or compressive force applied to the connection exceeds the frictional forces developed between the frictional surfaces, the main plate slips relative to either the brass insert plates in the case of the first type specimen or the outer steel plates in the case of the second. This process is repeated with slip in the opposite direction upon reversal of the direction of force application. Energy is dissipated by means of friction between the sliding surfaces. Application of cyclic loads of magnitude greater than the slip force results in approximately rectangular hysteresis loops. The earliest investigations of SBCs as energy dissipators date back to 1976 when a series of experiments were carried out at San Jose State University (SJSU) [1] on specimens similar in concept to those presented here. The term SBC used here is adopted from the report by T. F. Fitzgerald, et al. [3]. A number of other researchers have also investigated similar devices [2, 5].

Specimens and Experimental Results

To date, over forty SBC specimens of various bolt sizes, configurations and surface conditions have been tested at the University of California at Berkeley (UCB). Experimental results for specimens presented in this paper are representative of the salient SBC characteristics encountered throughout testing. Presented here are two specimens which are identical in every aspect with the exception that one includes shim like brass insert plates with a hole pattern matching that of the outer steel plates. Figures 1 and 2 show, respectively, the details of an SBC connection and the overall view of a typical assembled test specimen.

Both specimens are of A36 steel. The steel surfaces were cleaned to clean mill scale condition. The brass plates were of the widely available half hard cartridge brass variety (UNS-260). The test specimens were prepared by a local structural steel fabricator so as to simulate industry standards. Holes and slots in the steel plates were punched, and the edges were deburred. The two specimens described in this section are two bolt specimens. The bolts used were $\frac{1}{2}$ inch diameter, $3\frac{1}{2}$ inches long A325 bolts. The Belleville washers used were 8-EH-112 Solon compression washers. One such washer with a hardened washer on top was placed under each nut. Belleville washers are initially cone shaped annular disk springs which flatten when compressed. Earlier studies of SBCs [1] have shown that without the use of Belleville washers, and under large cyclic displacements, there is an almost immediate loss of bolt tension resulting in quick degeneration of the slip force. With the inclusion of Belleville washers, both turn of the nut and torque wrench methods of developing minimum bolt tension (70% of minimum tensile strength [11]) become inapplicable. To achieve the desired initial bolt tension, Direct Tension Indicator (DTI) washers were placed under each bolt head. DTIs are specially produced washers with protrusions pressed out of the flat surface. As the bolt is tightened, the compressive force exerted on the DTI flattens the protrusions and reduces the gaps between the flat portions of the DTI and the head of the bolt. The gaps can easily be measured with a supplied feeler gage. When the feeler gage fails to enter a specified number of gaps, the desired load in the bolt has been reached. DTIs used here were designed to indicate a bolt tension in the range of 12 to 14 kips.

The specimens, described above, were placed within an MTS loading frame as shown in Figure 3. The ram was capable of applying forces of 300 kips statically and 250 kips dynamically, with a maximum displacement stroke of 6 inches. Both displacement and force control were possible through a controller unit, and a function generator enabled the servoram to produce preprogrammed load or displacement histories. All testing was done under displacement control. Axial load and displacements in the specimen were measured through a load cell built into the MTS loading frame and a Linearly Variable Displacement Transducer (LVDT) built into the servoram. Axial force and displacement were monitored and recorded using a Data Acquisition System in conjunction with an IBM PC-AT computer. In addition, an X-Y plotter recorded load-displacement curves on paper for immediate visual observation of results.

Figures 4 and 5 show the applied displacement histories, force responses and the resulting hysteresis loops for the two selected tests. Figure 4, representing the case of friction between like clean mill scale steel surfaces, shows the main shortcoming of SBCs with friction between steel surfaces. As seen in the force response diagram, there is an almost immediate increase in the slip force followed by a quick drop to a magnitude several times less than the peak slip force. Although this behavior has not been observed in all tests of SBCs with friction between like steel surfaces, it has been present, to various extents, in the majority of cases. In tests with specimens where the mill scale steel surfaces were polished by wire brushing and those in which the surfaces were roughened and the mill scale removed by sand blasting, this behavior not only did not disappear but was actually intensified. The occurrence of this behavior in SBCs where friction occurs between steel surfaces renders such SBCs inefficient, at best, and impractical, at worst, as energy dissipators. Figure 5 represents the case of a SBC test with friction between clean mill scale steel and brass surfaces. As seen in Figure 5, the use of brass insert plates significantly reduces the variations in slip force magnitude observed in SBCs where friction occurs between steel plates, almost completely eliminating this undesirable behavior.

Discussion of Experimental Results

A discussion of experimental results involving friction must necessarily involve concepts of Tribology. Tribology is the body of science dealing specifically with friction, wear and lubrication. Terminology is a matter controversy in this field. The Tribological terminology used here is adopted from E. Rabinowicz's classic book "Friction and Wear of Materials" [9]. Friction is defined as "resistance to motion which exists when a solid object is moved tangentially with respect to the surface of another which it touches." Wear is defined as the "removal of material from solid surfaces as a result of mechanical action." Of the several types of wear discussed in Tribology literature, the two most relevant to the present discussion are adhesive wear and abrasive wear. Adhesive wear occurs when "two smooth bodies are slid over each other, and fragments are pulled off one surface to the other." These fragments may later return to the original surface or form into loose wear particles. Abrasive wear occurs when "a rough hard surface, or a soft surface containing hard particles, slides on a softer surface and ploughs a series of grooves in it." The material from the grooves generally forms into loose wear particles. Adhesive wear is almost universally present in all frictional phenomena, and it is the authors' belief that it, in conjunction with some abrasive wear, is the main mechanism of wear in the SBCs tested. In general, no one explanation can satisfactorily account for observed frictional behavior as many different mechanisms are involved in friction and wear processes, some simultaneous, some sequential and often interacting with each other. Presented here is a qualitative explanation of the experimentally observed SBC behavior based on the above mentioned Tribological notions and experimental observations. The explanation given here applies to both SBCs where friction occurs between like steels and where friction occurs between steel and brass. It is believed that as sliding is begun, wear particles are formed due to adhesive wear between the sliding surfaces. This results in outward displacement of the outer plates in the direction of the bolt axes. This in turn results in an increase in the bolt tension force and therefore an increase in the normal force between the sliding surfaces. As frictional force is directly proportional to normal force, this increase in the normal force is observed as an increase in the slip force. With continued sliding, a portion of the loose wear particles fall out of the connection, as observed experimentally, while the rest are either reabsorbed or act as abrasive particles contributing to abrasive wear. In Tribological terminology, the phenomenon that occurs here can be, simplistically, described as adhesive wear giving rise to wear particles which then cause additional abrasive wear. That abrasive wear occurs despite the smoothness of the original surfaces is evidenced by the appearance of sliding surfaces observed after the completion of experiments and upon the dismantling of the specimens. In the case of friction between like clean mill scale steel surfaces, both surfaces can be described as severely scratched. While in the case of friction between clean mill scale steel on brass, only the brass surface appears as scratched while the steel surface appears undamaged but with smears of brass. Scratched surfaces are a typical consequence of abrasive wear. The fall out and reabsorption of wear particles has the effect of reducing the bolt tension force as the outer plates now displace inward. This results in a reduction of normal force and is observed as a drop in the slip force. That the outer plates displace outward and then inward simultaneous with rise and drop in the slip force has been confirmed by measurements of the displacements of the outer plates along the axes of the bolts.

The above mentioned behavior, i.e. initial increase in slip force followed by a drop, observed in both Figures 4 and 5, although clearly far more poignantly evident in Figure 4, is directly attributed to the wear mechanisms mentioned above. The difference in behavior between the two types of specimens is solely due to the choice of the use of brass as a frictional surface, as the other two parameters known to influence adhesive wear, namely initial normal force and total travel distance, were identical for the two presented specimens. This choice was made precisely with the reduction of wear in mind. Brass is a common choice as a material frictionally compatible with low and medium carbon steels, and is often used in moderate cost applications where it is desired to reduce adhesive wear [9].

Application and Verification of Assumptions

As an illustration of the utility of SBCs as energy dissipators, consider the example structure shown in Figure 6. A SBC with a slip force of 60 kips connects the diagonal brace to the main structure. Analysis of the structure was performed using the DANS [10] computer program. Newmark's step-by-step integration method was used. The structure was assumed to behave as a shear structure, and the SBC was assumed to behave as an elastic-perfectly-plastic connection. Viscous damping was assumed to be 2%. Responses due to four acceleration histories were calculated. The acceleration histories were as follows: the 1971 Pacoima Dam earthquake S16E, the 1952 Taft earthquake N21E with magnification factor of 5, the 1940 El Centro earthquake S00E with magnification factor of 2 and the 1987 Whittier earthquake N00E, at Sylmar, with magnification factor of 40. Figures 7, 8, 9 and 10 show ground acceleration histories, structure displacement responses and energy diagrams for each applied history. The columns remain elastic at all times and the SBC prevents the buckling or yielding of the diagonal brace. An examination of the energy diagrams reveals that on the average close to 85% of the total input energy is dissipated by the SBC.

To verify the validity of the assumption of elastic-perfectly-plastic behavior for SBCs with brass insert plates and to observe the response of such an SBC to displacement histories more realistically representing response to actual earthquakes, an SBC specimen was designed to slip at 60 kips. Based on previous results from tests of specimens with two $\frac{1}{2}$ inch diameter A325 bolts, a test specimen with eight $\frac{1}{2}$ inch A325 bolts was fabricated. The specimen was subjected to SBC slip displacement responses derived from the above mentioned analyses. The four SBC slip displacement response histories were applied consecutively, in the order of acceleration histories mentioned above, to this specimen. Figures 11, 12, 13 and 14 show SBC slip displacement response histories and analytical and experimental hysteresis diagrams for each acceleration history. It is seen that the target slip force of 60 kips is attained almost perfectly in response to the first displacement history. As expected, the slip force drops, although not significantly, for the next three applied displacement histories. The rectangular shape of the hysteresis loops, coupled with the reasonably constant slip force, indicates that the assumption of elastic-perfectly-plastic behavior for SBCs with brass insert plates is a valid one.

Concluding Remarks

Both SBC types have been shown capable of dissipating significant quantities of energy as judged by the areas enclosed by the experimentally arrived at hysteresis loops. Slip force in SBCs where friction occurs between like steel plates has been shown to vary significantly. The peak slip force for such SBCs occurs almost immediately and may be several times the magnitude of the mean slip force. As such, for this type of SBC to dissipate energy throughout the course of ground excitation, either the members supporting the SBC must be designed with excessively large safety factors or the SBC itself must be under-designed. On the other hand, in SBCs where because of the brass insert plates friction occurs between brass and steel, slip force has been shown to remain relatively constant over the range of interest. It has also been shown that such SBCs behave in nearly perfect elastic-perfectly-plastic manner. In view of these results, it is evident that SBCs with steel on brass frictional surfaces possess significant advantages in terms of efficiency as energy dissipators and ease of modelling. As such, and with low material and fabrication cost, these SBCs exhibit great potential as an alternative choice for energy dissipation in seismic design and retrofit of structures.

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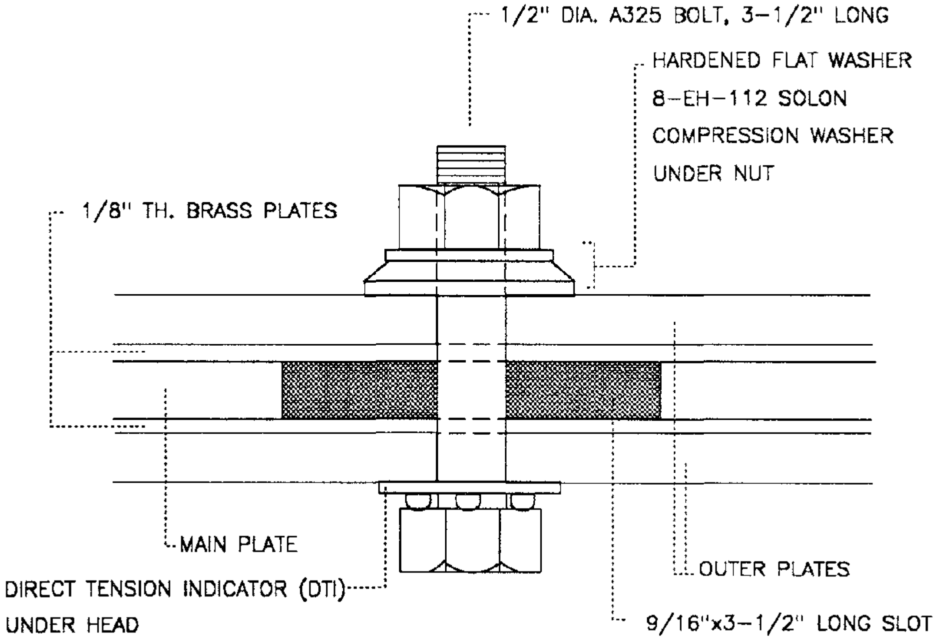
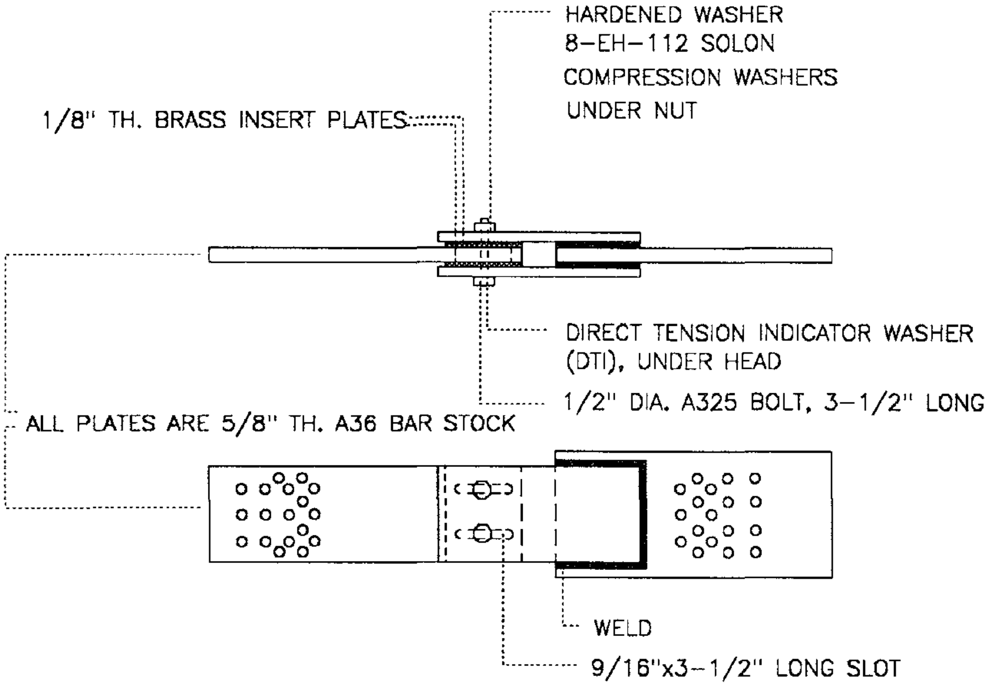


Figure 1



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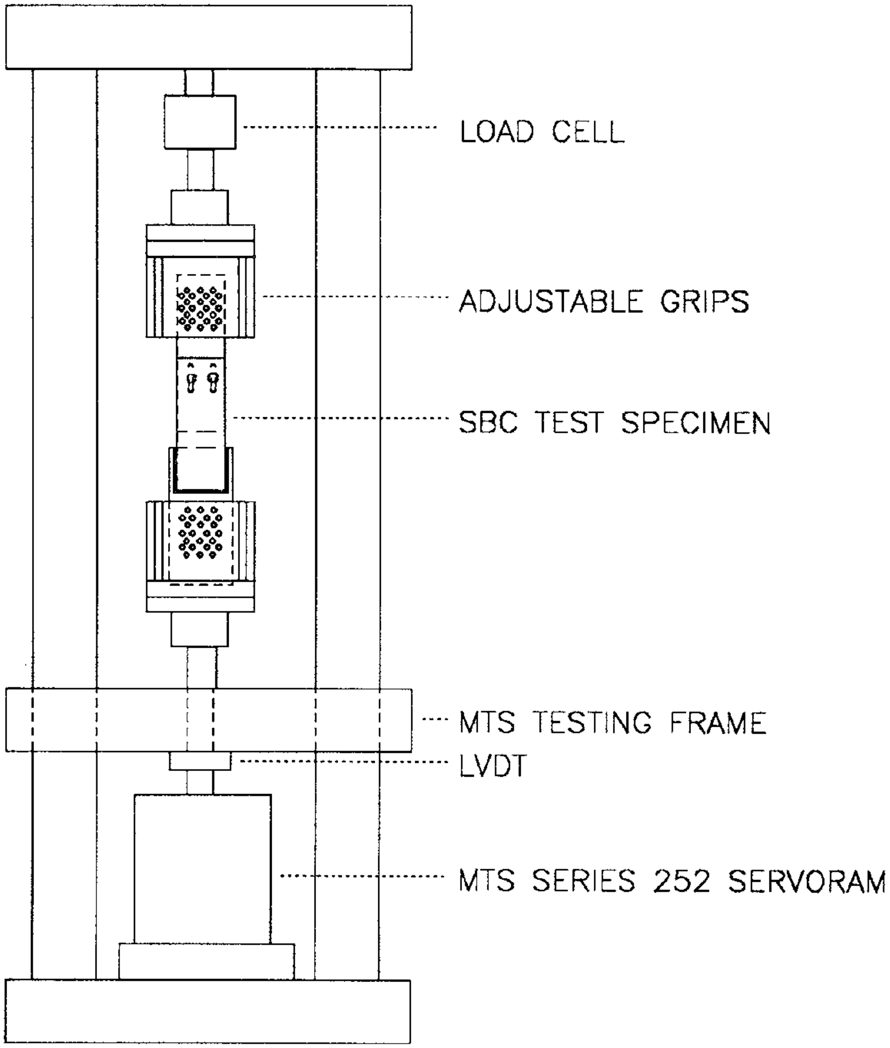
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Figure 3

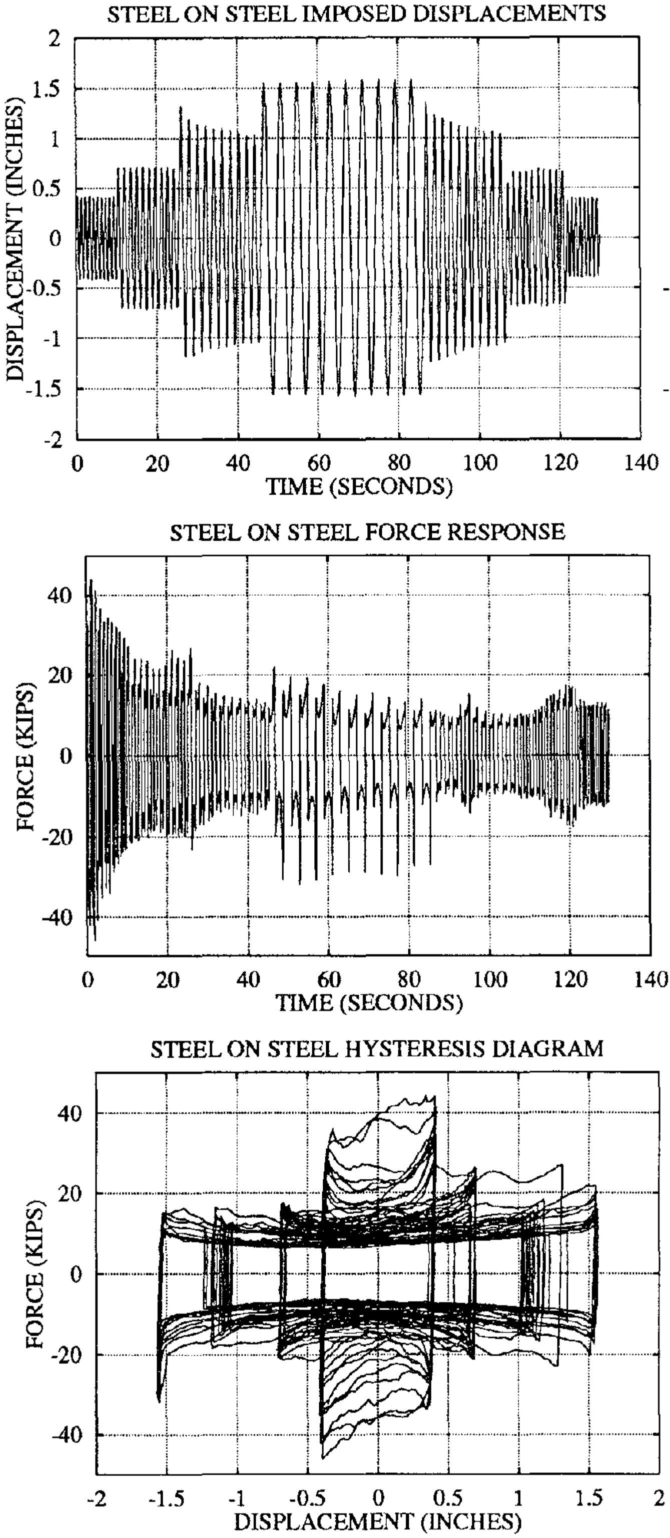


Figure 4

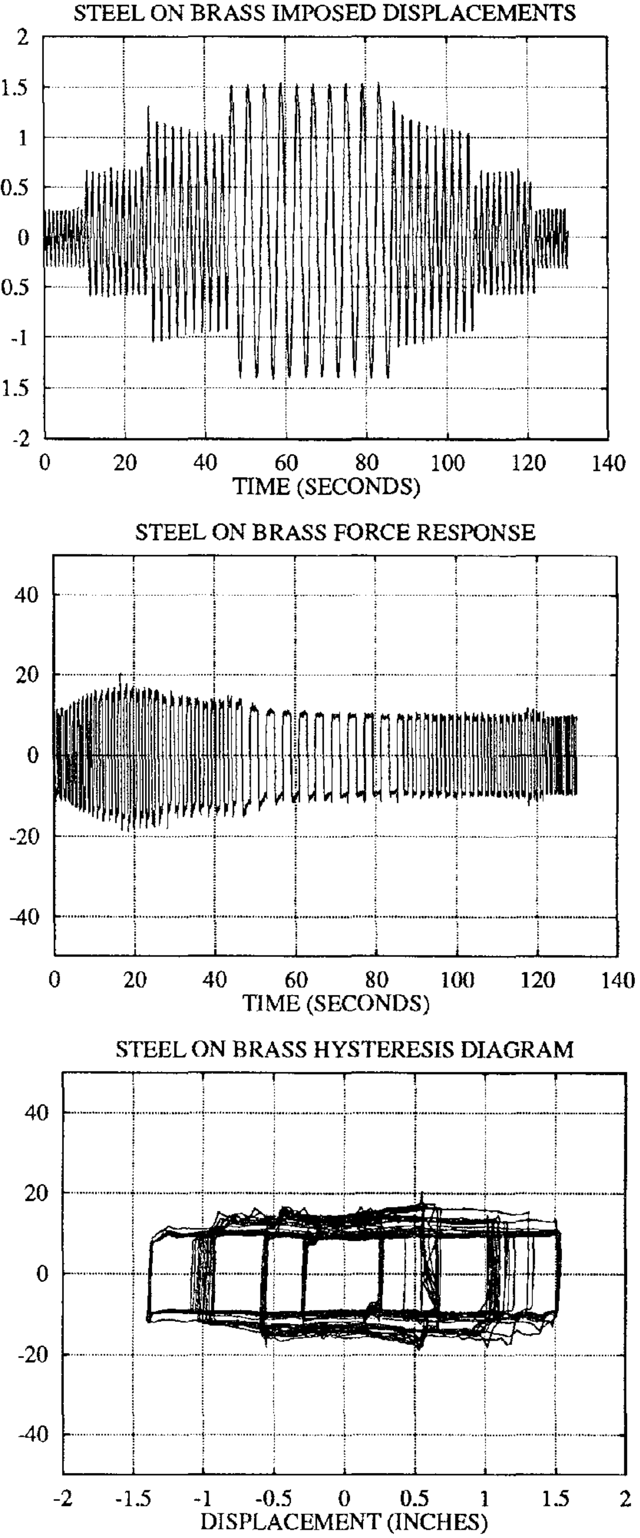
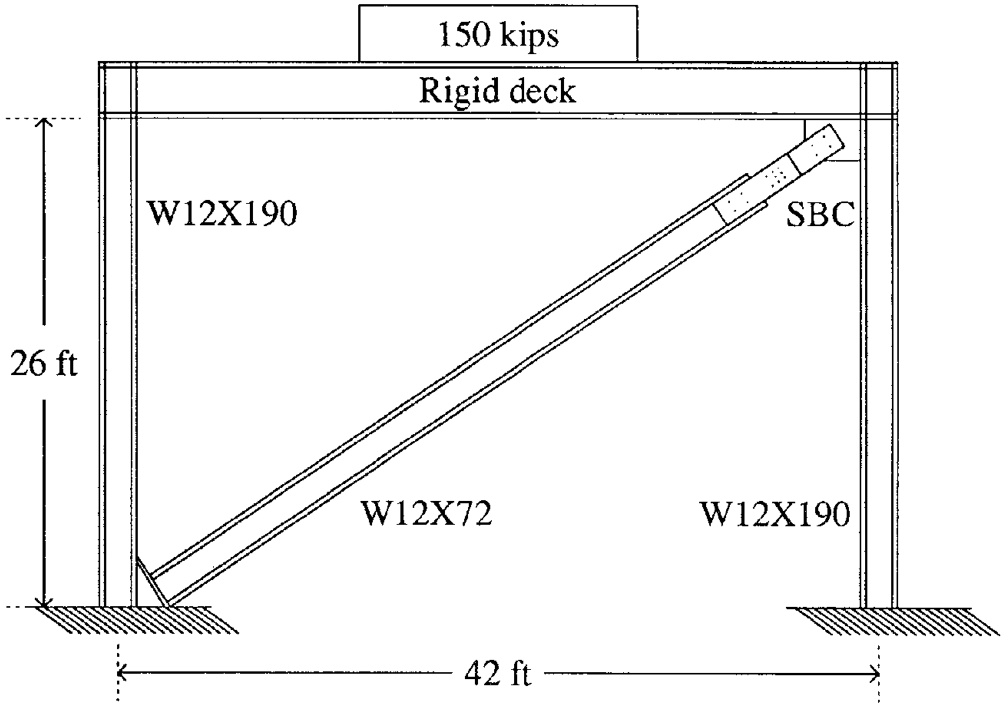


Figure 5

Note: 1 Inch = 25.4 mm, 1 Kip = 4.45 kN.



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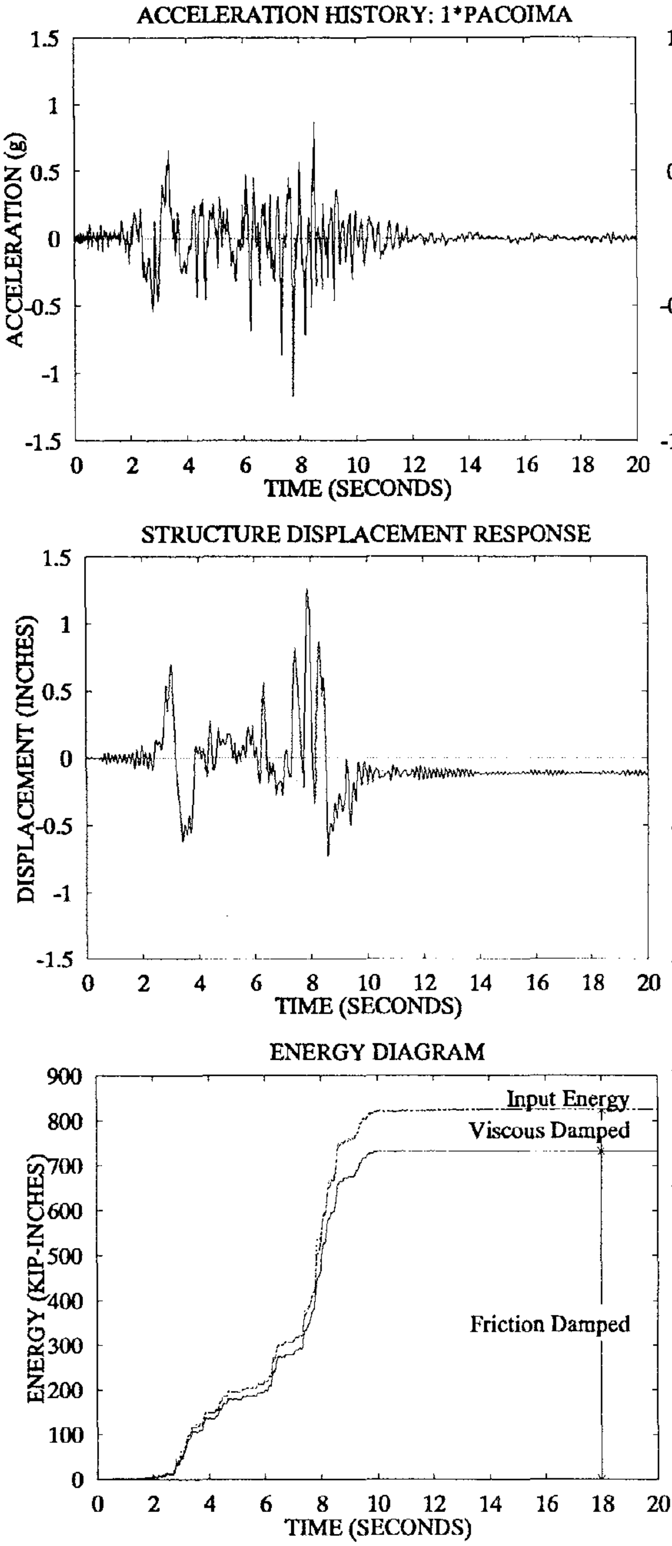

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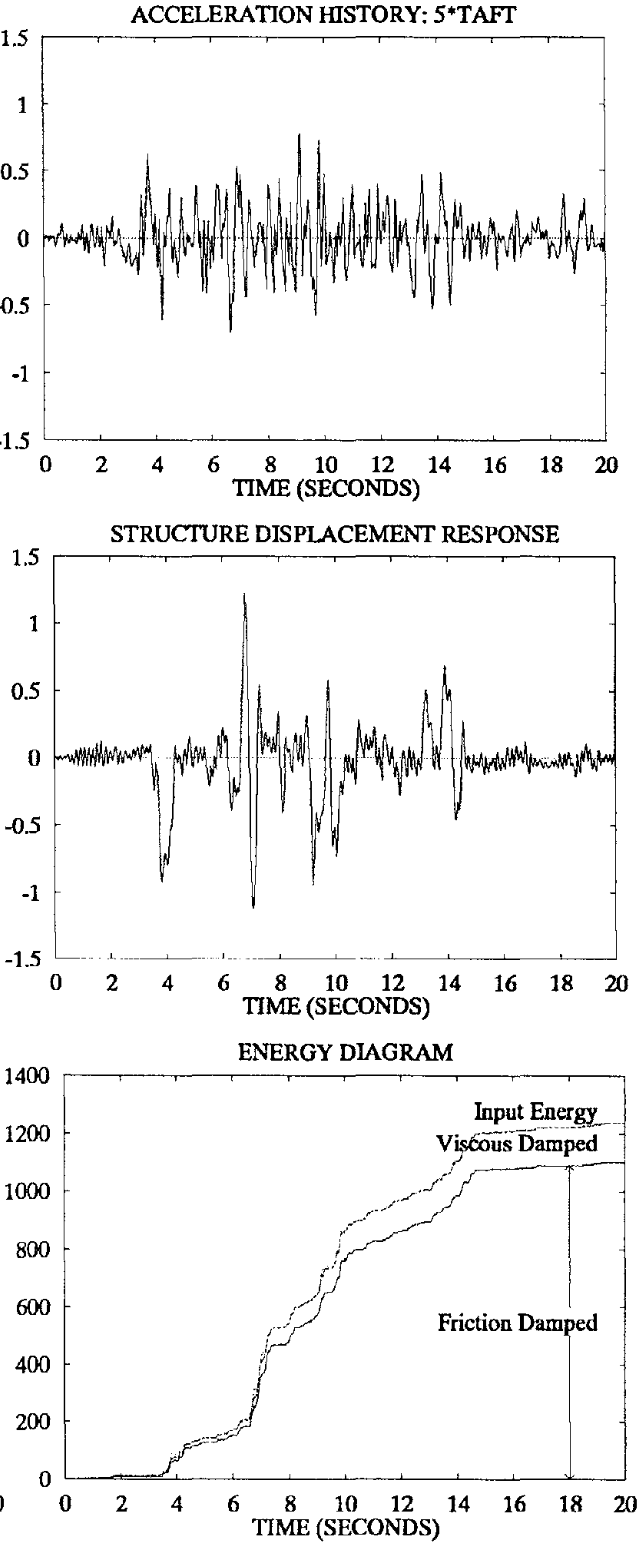

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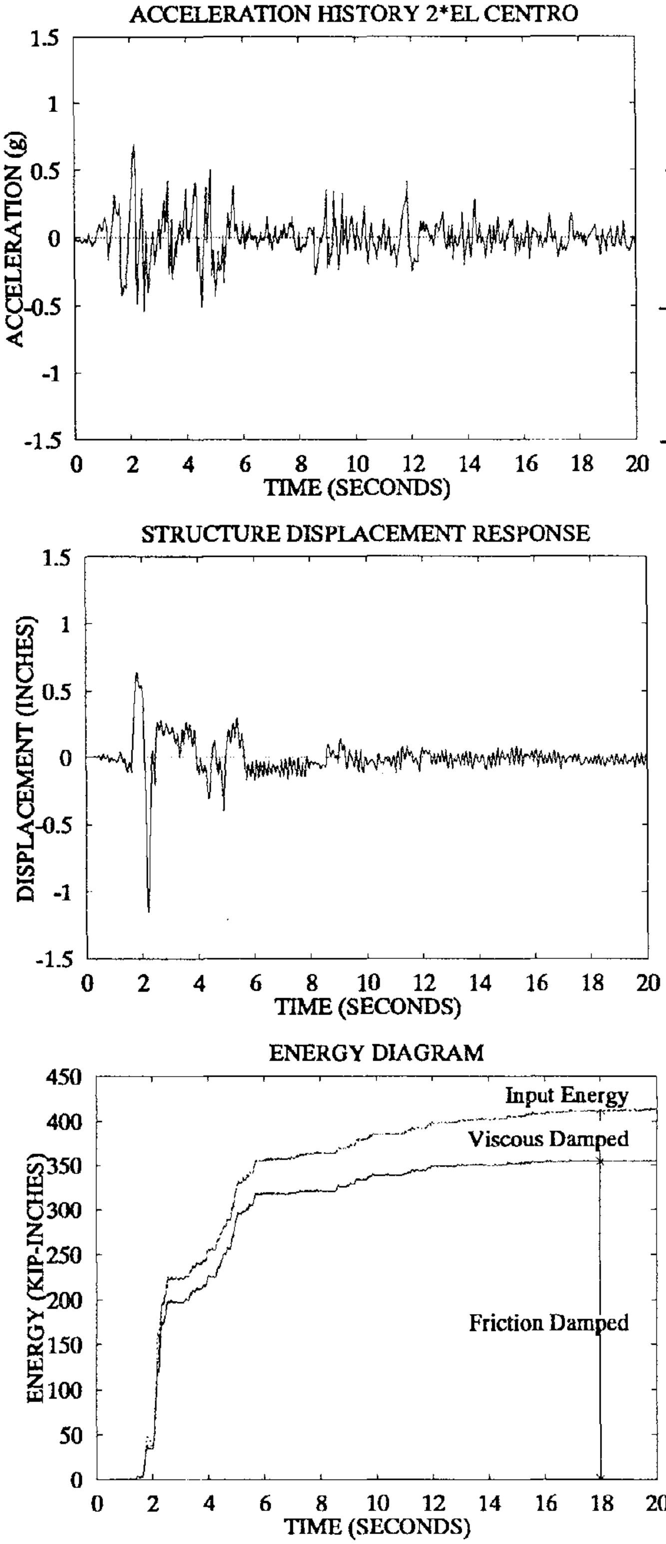
Note: 1 Inch = 25.4 mm, 1 Kip = 4.45 kN.



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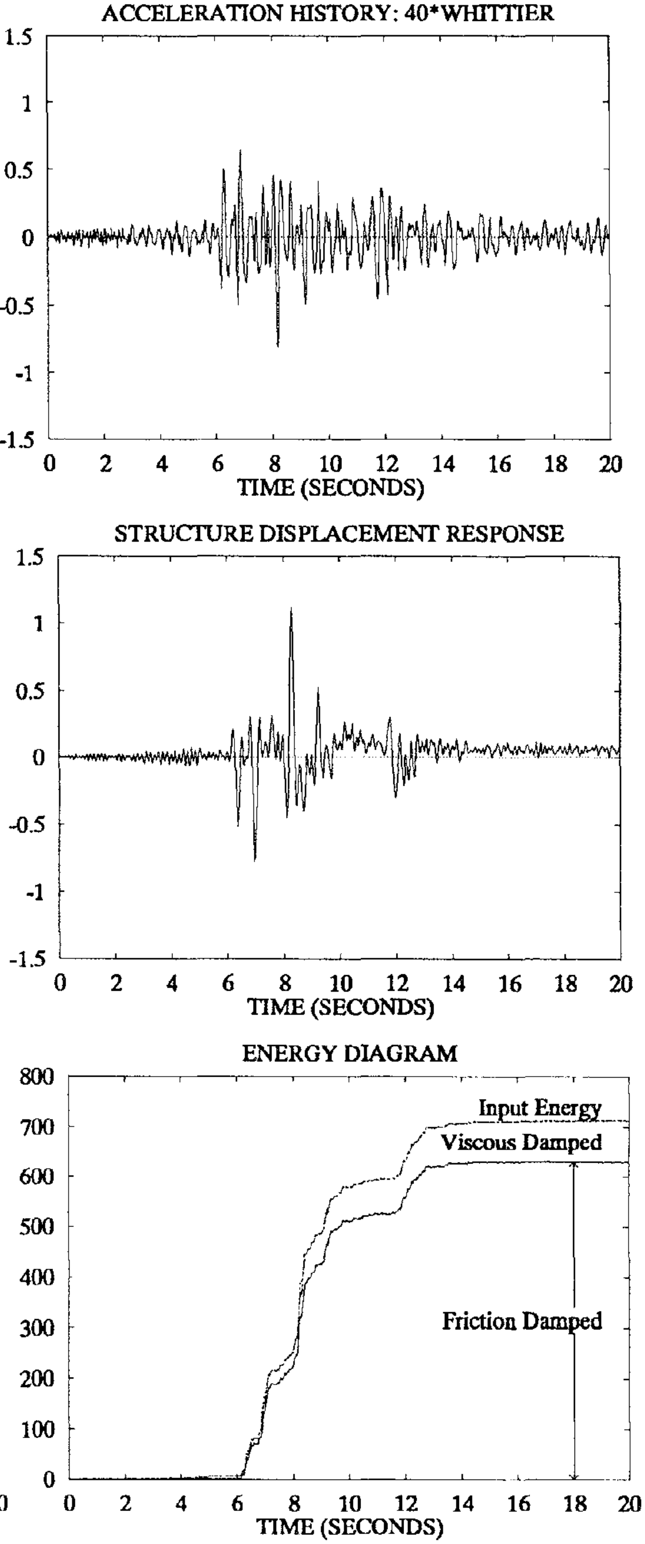

Figure 10

Note: 1 Inch = 25.4 mm, 1 Kip = 4.45 kN.

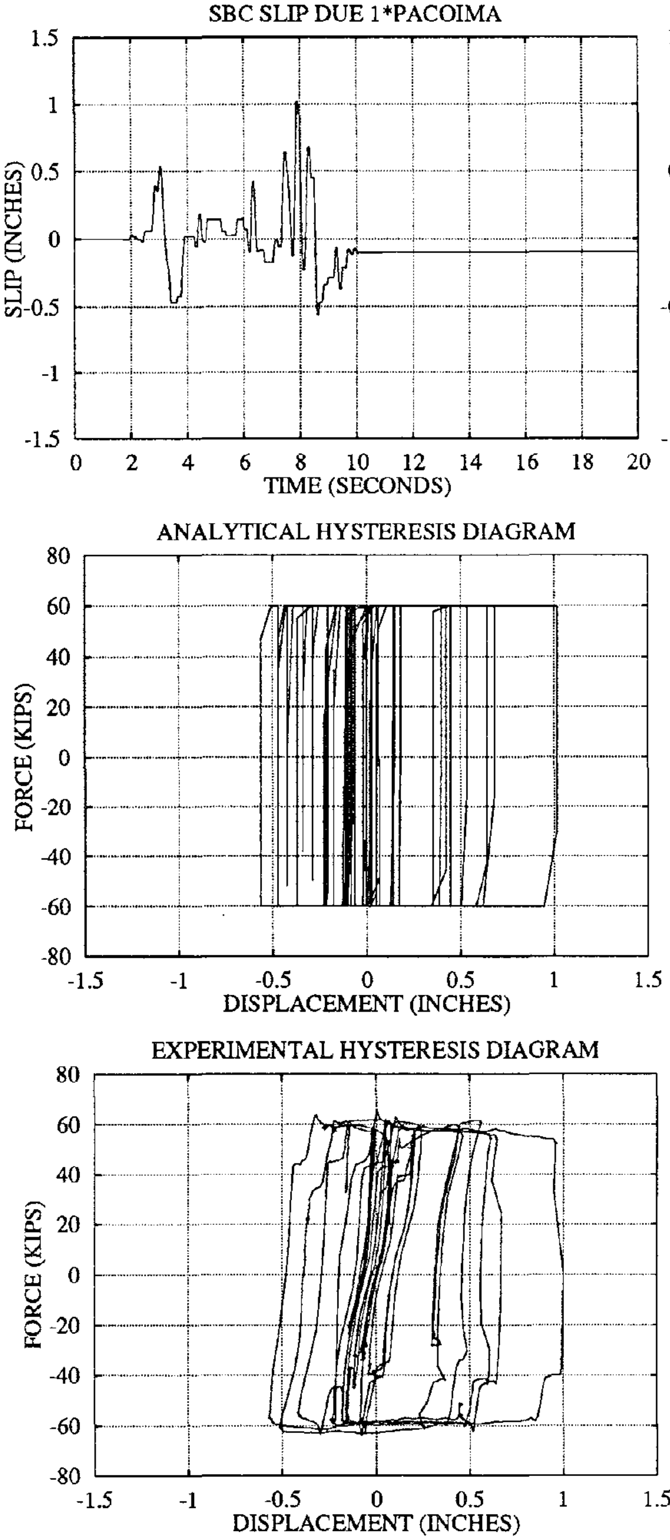

Figure 11

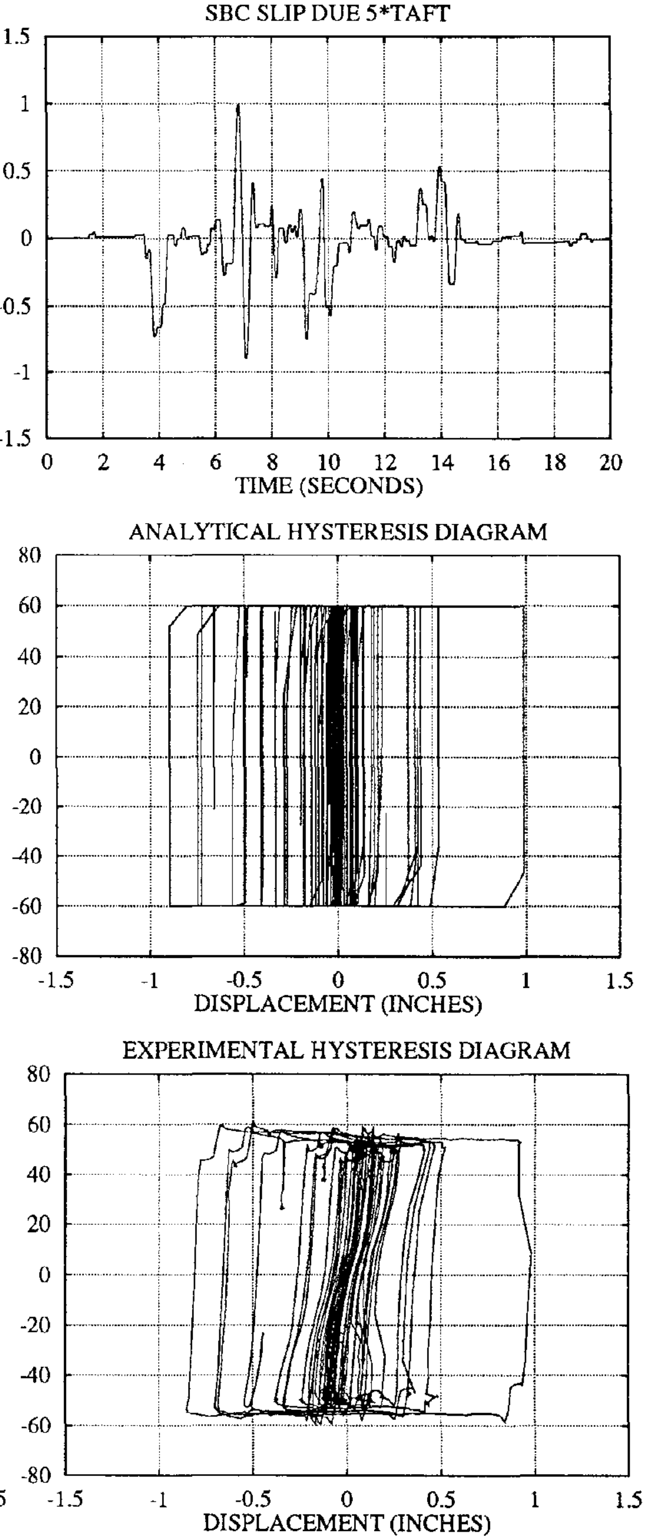

Figure 12

Note: 1 Inch = 25.4 mm, 1 Kip = 4.45 kN.

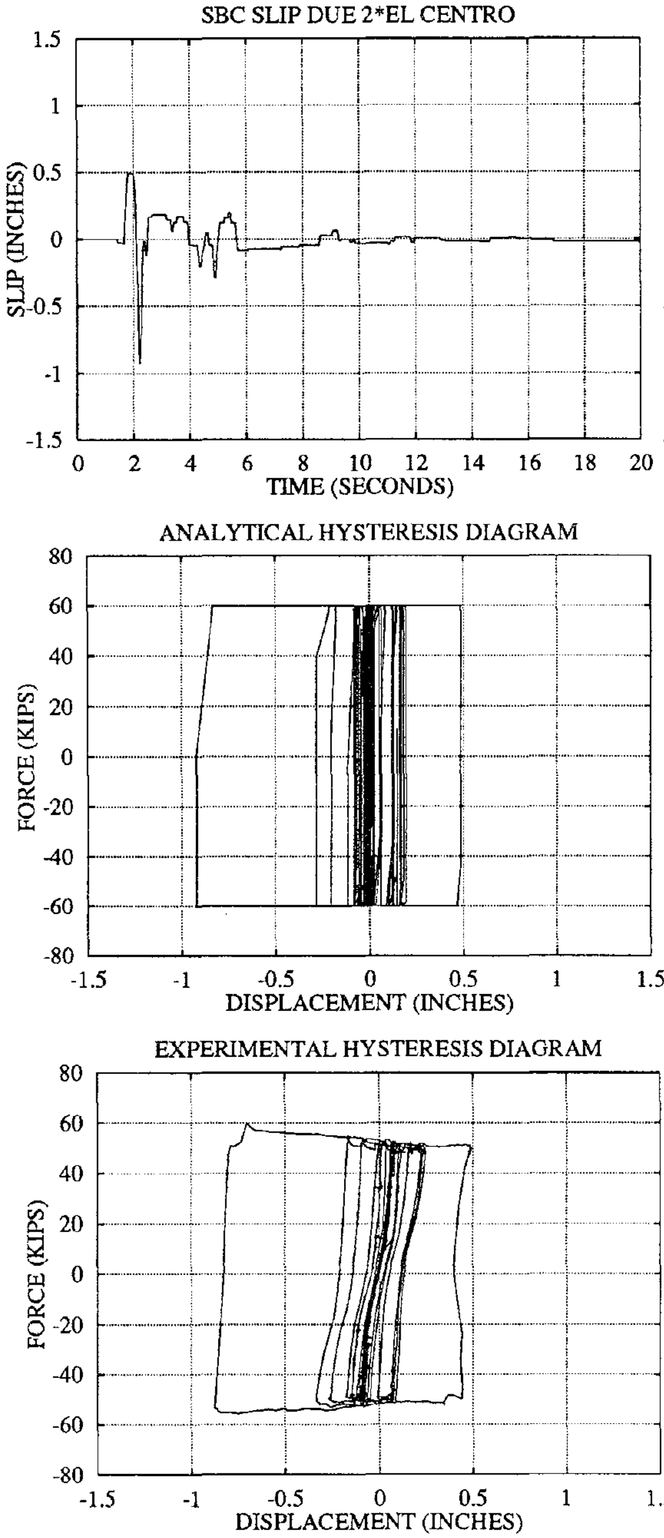

Figure 13

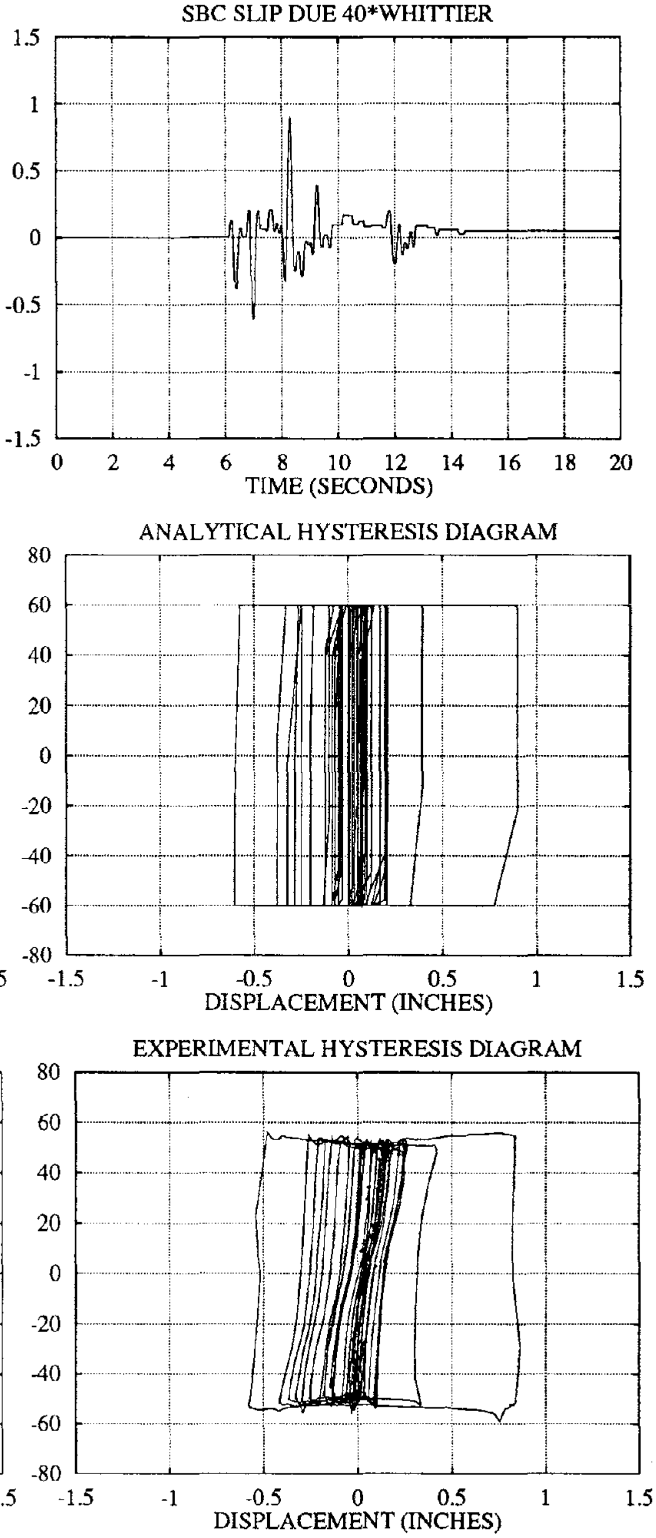

Figure 14

Note: 1 Inch = 25.4 mm, 1 Kip = 4.45 kN.

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