EFFECTS OF DEFORMATION SOFTENING ON SEISMIC BEHAVIOR OF STEEL MOMENT FRAMES

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ABSTRACT :

Engineers have become increasingly concerned about the potential effects of various forms of deterioration that may be experienced by moment-resisting frame structures during severe seismic excitations. The brittle connection fractures experienced by a number of welded steel moment-resisting frame structures during recent earthquakes have been the most extensively studied to date. However, recent cyclic testing of beam-column connections into the inelastic range demonstrates that connections may suffer other, more ductile forms of deterioration. Negative post-yield tangent stiffness, hereafter referred to as deformation softening, is of particular interest due to its potentially adverse effects on system behavior. The effects of deformation softening were examined as part of an integrated experimental and analytical investigation of the effects of various forms of hysteretic deterioration on steel moment frame system behavior. The experimental portion of this study consisted of a series of shaking table tests performed on a one-third scale, two-story, one bay, steel moment frame with idealized, mechanical connections. These tests and subsequent analytical studies show that, in general, significant loss of connection strength capacity, whether from deformation softening or other types of deterioration, leads to large peak and residual drifts and, for large pulse excitations with durations longer than the fundamental period of the structure, may cause collapse. Deformation softening was found to have substantial adverse effects on system behavior in many cases.

KEYWORDS: post-yield, stiffness, collapse, hysteretic, earthquakes

1. INTRODUCTION

In the aftermath of the 1994 Northridge, California earthquake, brittle fractures were discovered at the beam-column connections of a number of steel moment frames in the greater Los Angeles area (Bertero, 1994). These connections had been previously assumed to be very ductile, and the discovery led to numerous studies on the causes of the fractures and on ways of preventing them (FEMA, 2000a,b). This research led to the development of a number of new, post-Northridge connection designs that were not prone to brittle fracture. However, these new designs displayed other forms of hysteretic deterioration during testing that involved repeated cycling into the inelastic range (FEMA, 2000b). One of the most interesting forms of hysteretic deterioration observed during these studies, and which may have significant potential impact on system behavior, is deformation softening, or negative post-yield stiffness. Examples of deformation softening observed in tests of post-Northridge beam-column connections are shown in Figure 1.

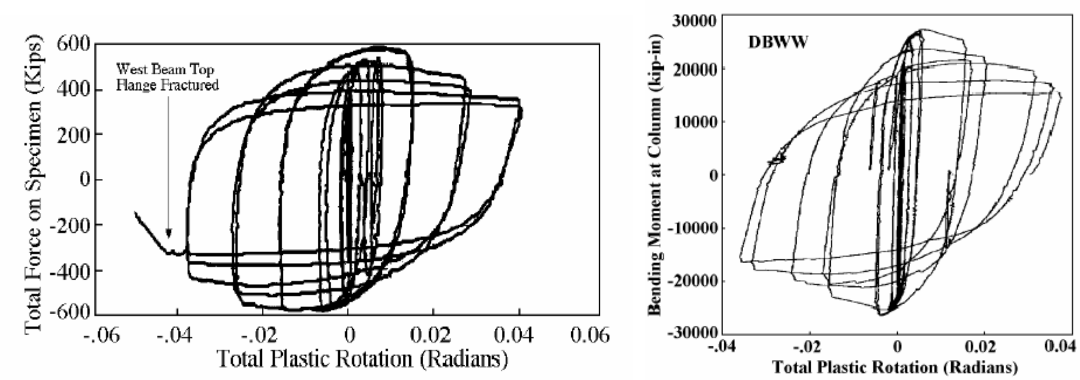

Figure 1. Deformation softening in post-Northridge beam-column connection tests reported in FEMA 355-D (FEMA, 2000b). Note the negative post-yield slope, particularly in the first several large inelastic cycles.

2. BACKGROUND

Deformation softening is defined as the presence of negative post-yield stiffness in the connection hysteresis. Negative post-yield stiffness typically results from local buckling of the beam in the plastic hinge zone. Deformation softening is distinct from the other major types of ductile hysteretic degradation, namely cyclic strength degradation (isotropic softening) and stiffness degradation (reduction in reloading and/or unloading stiffness) in several important ways. The first important difference is that significant strength loss occurs within a single cycle, which can occur during the first large inelastic excursion as shown in Figure 1. This rapid within-cycle degradation increases the vulnerability of these connections to large near-field ground motions, in which the majority of the seismic demand occurs in one or two cycles of motion. The other two types of ductile hysteretic degradation, which also occur in the tests in Figure 1, only begin to significantly affect connection properties after several large inelastic cycles. The second important difference is that deformation softening in enough connections simultaneously can lead to a negative slope in the global base shear–interstory drift hysteresis, which can in turn lead to dynamic instability. Any contributions to global instability have the potential to combine with P-delta effects in an additive way, exacerbating the effects of large deformations.

Only a few prior analytical studies have examined the effects of negative post-yield stiffness (Rahnama and Krawinkler 1993; Mahin and Morishita 1998). This is primarily due to the fact that until relatively recently, limitations in the software commonly used for nonlinear dynamic analysis of frame systems necessitated that investigators confine their analyses incorporating negative post-yield stiffness to single degree-of-freedom (SDOF) systems only. The studies by Mahin and Morishita (1998) show that deformation softening can increase ductility demand, particularly in the short period range, and that it can lead to the accumulation of displacements in one direction, called "ratcheting". The studies by Rahnama and Krawinkler (1993) show that deformation softening has significant adverse effects on system behavior, and that softening systems cannot achieve the same ductility as systems without softening unless the strength of the softening system is greatly increased. [It should be noted here that Rahnama and Krawinkler's study explicitly considered P-delta effects rather than connection deformation softening, but they considered P-delta by using a hysteretic loop with negative post-yield stiffness, making the study directly applicable to the problem at hand.] More recent studies of ductile deterioration (Ibarra and Krawinkler, 2005, Lignos and Krawinkler, 2007) show that the presence and severity of deformation softening are important contributing factors to collapse.

This is the first study to examine the effects of deformation softening on overall structural response in a comprehensive fashion, using experimental studies to validate findings based on analytical simulations. Deformation softening was examined as part of a larger integrated experimental and analytical investigation into the effects of various forms of hysteretic deterioration on the overall system behavior of moment resisting steel frames, including brittle fracture (Rodgers and Mahin 2004). This paper presents only those results that pertain to deformation softening.

3. EXPERIMENTAL AND ANALYTICAL SETUP

3.1 Experimental Specimen and Plan

The specimen employed in the experiments is a one-third scale, two-story, one-bay moment frame. Plastic hinge regions at the ends of each beam were represented by idealized mechanical connections (van Dam 2000, Rodgers et al., 2006), which were designed to reproduce, repeatedly and dependably, a wide variety of hysteretic characteristics, including ideally ductile behavior and deformation softening (negative post-yield stiffness), which are shown in Figure 2. The remainder of the frame was designed to remain elastic. The specimen, shown in Figure 3, has columns spaced at 2.74 m (9.0 ft), floor heights of 1.37 m (4.5 ft), and an elastic fundamental period of approximately 0.65 seconds. To simplify testing and interpretation of results, pin ended (clevis) connections were used at the base of each column. Two simple pin-ended frames were placed parallel to the moment frame as shown Figure 3, one on each side. These frames supported the inertial reactive mass and provided out-of-plane bracing but did not contribute in-plane stiffness or moment resistance. Slack wire cables in the in-plane direction provided a mechanism to catch the test specimen in the event that it collapsed during testing. More information on the test setup may be found in Rodgers and Mahin (2004).

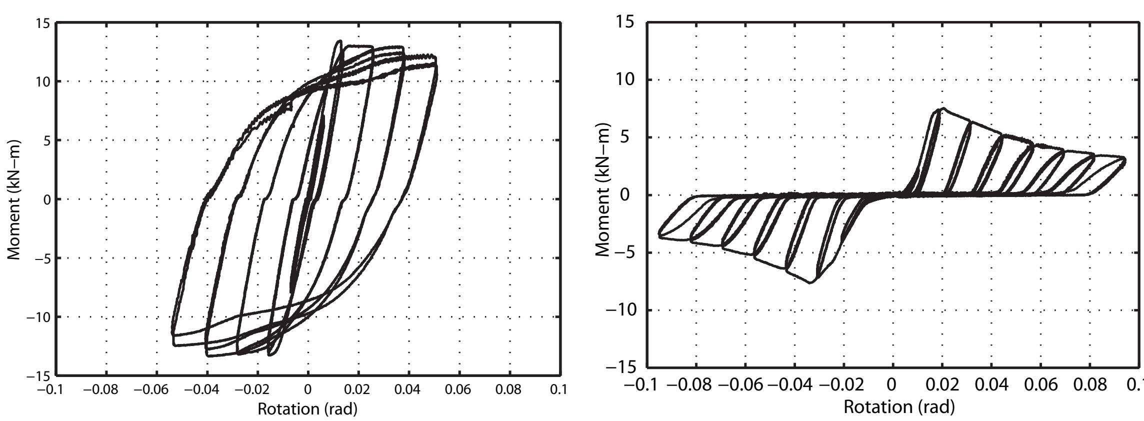

Figure 2. Idealized mechanical connection with ductile baseline (left) and deformation softening (right) hysteretic behavior

Experiments were carried out with the arrangements of the ductile baseline and deformation softening connections shown in Figure 4, considering several different acceleration time histories imposed horizontally at the base of the test frame. Connections with deformation softening behavior are denoted by gray circles, with ductile baseline connections at the other connections, if applicable. Configurations of interest include the case where all connections have ideally ductile behavior, and cases where deformation softening occurs in one or both stories. Deformation softening at the connections was achieved by buckling of the compression coupon. Nuts were not installed on the outside of the coupons only, preventing them from resisting tension. Component testing showed that if coupons were permitted to straighten under tension, strain hardening would cause a positive net positive post-yield slope even with severe buckling of the compression coupon (van Dam, 2000). This design necessity also led to the extremely pinched hysteretic behavior shown in Figure 2. Due to the near-field pulse excitations used, however, the behavior of the specimen was controlled by the negative post-yield stiffness of the connections, rather than by pinching.

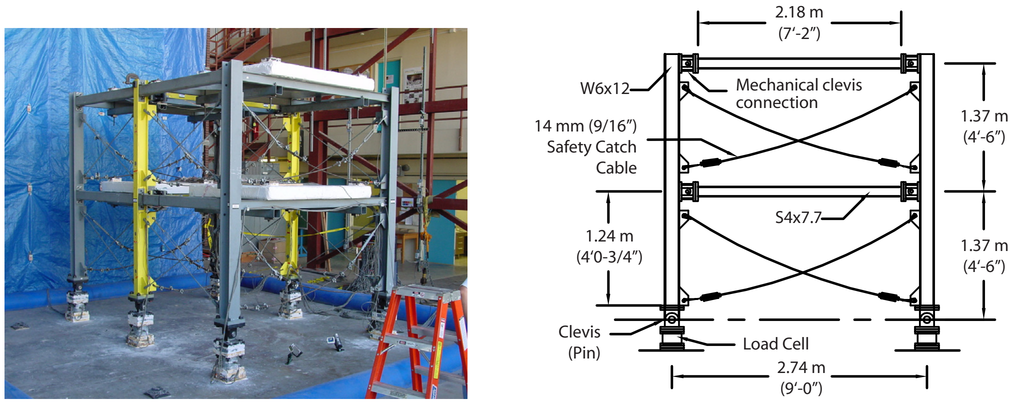

Figure 3. Experimental specimen on shaking table (left) and engineering drawing of main frame (right)

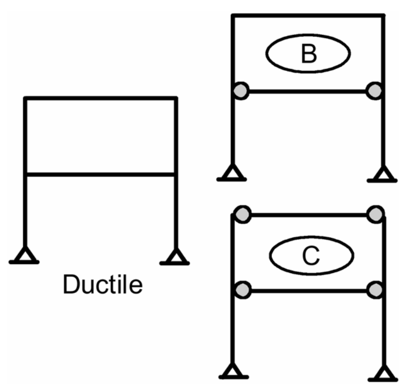

Figure 4. Connection configuration patterns of interest, where gray circles denote softening connections

For the configuration patterns of interest, two simplified cosine acceleration pulse earthquake excitations were used, representing idealized fault-normal near-source ground motions. The first cosine pulse was 0.6 s in duration, about the same as the fundamental period of the test specimen (0.65 s). The second cosine pulse was 1.2 s in duration, about twice the fundamental period.

3.2 Analytical Model

A two-dimensional analytical model of the experimental specimen was developed using OpenSEES (McKenna, 2003), an open-source computational framework for nonlinear static and dynamic structural analysis. The idealized mechanical connections were modeled as nonlinear zero-length springs, with general hysteretic and steel material models (see Mazzoni et al. 2003) used to model the moment-rotation relations for fracture and ductile baseline behavior, respectively. The remainder of the frame was modeled with elastic beam-column elements because the test data confirmed that nonlinearity was confined to the connections. Further details of the analytical modeling assumptions and procedures used are available elsewhere (Rodgers and Mahin 2004). The analytical model was used in direct comparisons to the specific shaking table experiments performed, and in a parametric investigation that examined the effects of various hysteretic and excitation characteristics.

4. EXPERIMENTAL AND ANALYTICAL RESULTS

The results of the experimental and analytical portions of the study are integrated in this section to improve the understanding of the effects of deformation softening itself as well as its interactions with various excitation and connection hysteretic parameters. The general effects of deformation softening are discussed first, and followed by the effects of other parameters. Parameters discussed include the number of degrading connections, excitation amplitude and frequency characteristics, and hysteretic characteristics such as post-yield tangent stiffness. Hysteretic characteristics examined by analysis are defined in Figure 5.

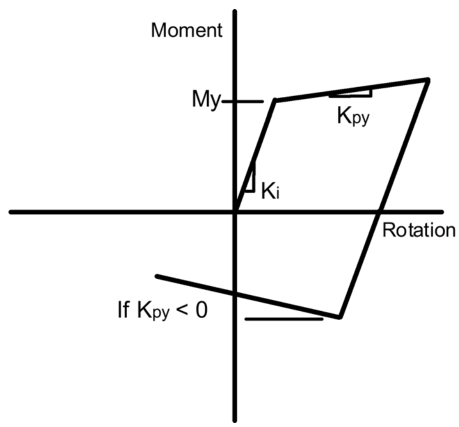

Figure 5. Definition of connection moment-rotation hysteretic characteristics examined by analysis, where K_i denotes initial elastic slope, K_{py} denotes post-yield tangent slope, and M_y denotes yield moment.

4.1 Effects of Deformation Softening on System Behavior

When buckling initiates, the moment capacity of the connection begins to decreases substantially. This causes a subsequent decrease in the measured base shear response of the structure, as shown in Figure 6. The response shows one of two trends: the base shear either (a) initially increases and then plateaus or (b) plateaus immediately before decreasing, depending on the relative number of deformation softening and ductile connections. Increase-then-plateau behavior occurs in the B pattern case, which has two ductile connections in the second story that are still in the elastic range when softening initiates in the first story. Because the second story connections have not yielded, they are able to resist additional moment as displacement demands increase. Plateau-then-decrease behavior occurs when all connections begin to soften simultaneously (the C pattern case), and there is no reserve capacity to resist additional demand. After the plateau, the base shear begins to decrease as the connections lose moment capacity. This within-cycle loss of strength is caused by buckling of the compression coupons. The severity of buckling and the rate at which it occurs determine the post-yield tangent stiffness. The duration of the buckling excursion, which depends on the excitation, combined with the post-yield tangent stiffness determines the amount of strength lost in the cycle. The rate of base shear decrease depends on the post-yield tangent stiffness of the connections as well as the number of softening connections. No sudden changes are observed in the displacement response at the onset of buckling, as shown in Figure 6 for the 1.2 second pulse case. The deformation softening cases show significant period elongation when compared to the ductile cases. Also, the maximum interstory drift ratios are greater for the cases with deformation softening than for cases with ductile connection behavior.

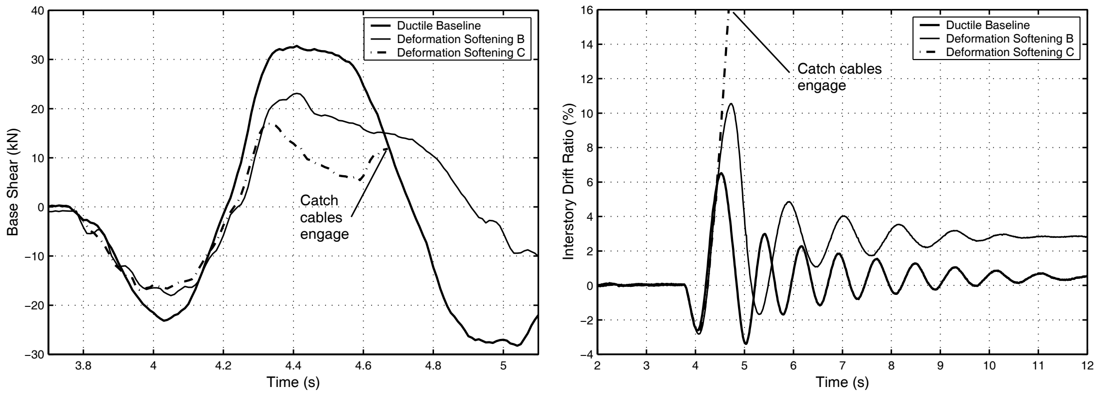

Figure 6. Base shear response (left) and interstory drift (right), 1.2 s cosine pulse excitation

4.2 Effects of Excitation Amplitude

The effects of excitation amplitude were examined analytically using incremental dynamic analyses (IDAs) (Vamvatsikos and Cornell, 2002). In these analyses, the computer model of the specimen was repeatedly subjected to the same excitation with increasing amplitude. Figure 7 shows the results for the 1.2 second cosine pulse excitation, where an amplitude scale factor of 1 corresponds to the amplitude of the excitation during the shaking table experiments. The IDAs show that maximum interstory drift response generally increases with increasing excitation amplitude, with exceptions occurring when increasing amplitude causes a change in the failure mode or in the failure location within the time history, which in turn leads to a locally reduced response. Further increases in amplitude reverse this trend and again cause increased response.

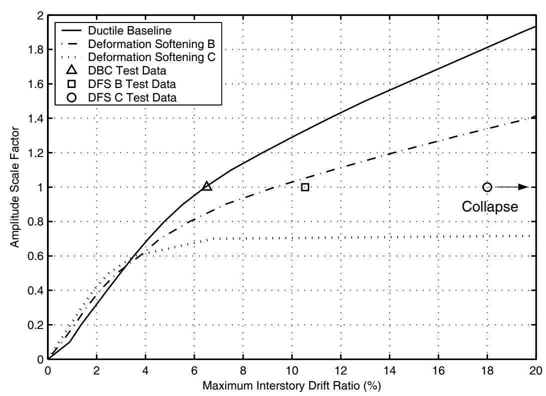

Figure 7. Incremental dynamic analyses showing effects of amplitude for the 1.2 s cosine pulse excitation

4.3 Effects of Number of Deteriorating Connections and Deterioration Severity

The number of connections that display deformation softening behavior has significant effects on the response of the specimen. Figure 6 shows that the case with all connections deteriorating (the C pattern) has a much larger decrease in strength and much larger maximum and residual displacements (it suffers collapse) than the B pattern, which has half as many deteriorating connections. An increase in the number of deteriorating connections adversely affects behavior because it greatly increases the sensitivity to post-yield tangent stiffness. The analytical results in Figure 8 demonstrate this effect. The C pattern case displays large maximum drifts and/or collapse once the post-yield tangent stiffness ratio K_{py}/K_i becomes more strongly negative than -0.02 (negative two-percent). The B pattern, with only half of the connections softening, is relatively insensitive to the post-yield tangent stiffness. The two ductile connections provide reserve capacity, which reduces global strength loss and prevents dynamic instability. Tests with fracturing connections showed that the number of fractures has very similar effects on sensitivity to post-fracture tangent stiffness (Rodgers and Mahin, 2006).

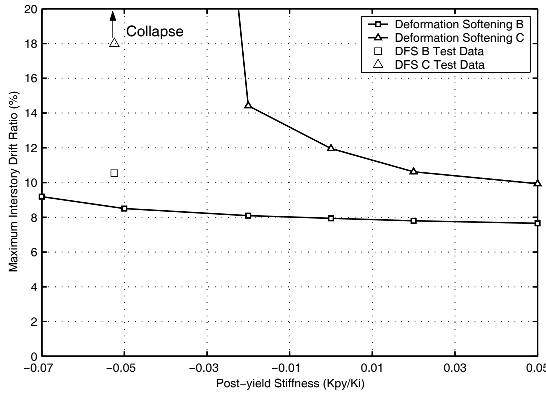

Figure 8. Effects of number of softening connections and post-yield tangent stiffness ratio

The sharp increase in interstory drift for the C pattern when K_{py}/K_i is more strongly negative than negative two-percent (-0.02) suggests that there may be a threshold level of negative tangent stiffness, beyond which the specimen becomes unstable (if all connections have the same tangent stiffness) for the excitation employed. Incremental dynamic analysis using the 1.2 second cosine pulse excitation shown in Figure 9 indicates that potential threshold levels are dependent on excitation amplitude.

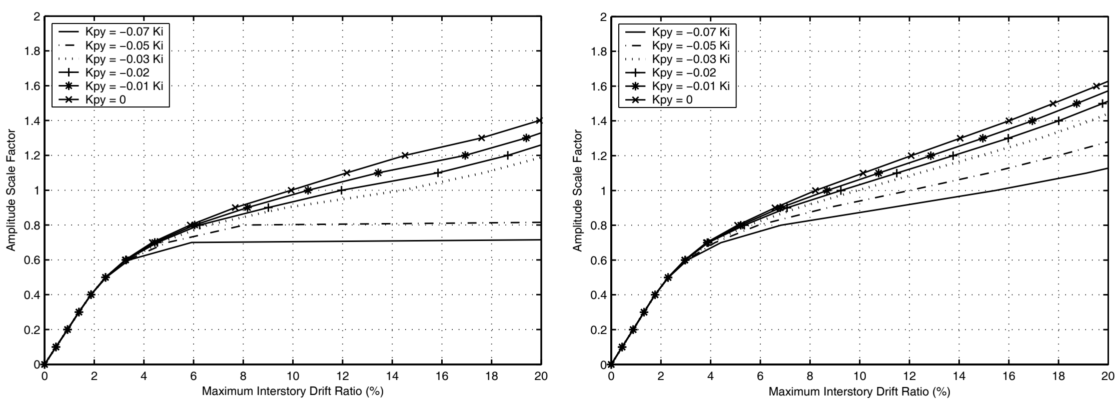

Figure 9. Incremental dynamic analysis of DFS C pattern with variable K_{py} with (left) and without (right) P-delta effects, 1.2 second cosine pulse

The potential combination of the negative tangent stiffness in the connection hysteresis and the globally negative tangent stiffness contributed by P-delta effects was examined analytically. IDAs with P-delta effects included via the corotational formulation (used to accurately model large deformations) were compared to those without P-delta effects. Figure 9 shows the increase in peak drifts caused by P-delta effects. In particular, the cases with more strongly negative values of K_{py} were prone to instability at lower levels of excitation amplitude. In contrast, the ideally ductile case in Figure 7 does not reach a similar instability point, though P-delta effects are included (also via the corotational formulation). These results indicate that the presence of negative post-yield tangent stiffness interacts with P-delta and reduces the interstory drift at which the structure becomes unstable, in some cases substantially. For this flexible specimen with stiff columns, the interaction between negative post-yield stiffness and P-delta effects is observed at large drifts. It is anticipated that such effects will be observed at significantly smaller drifts in structures more susceptible to P-delta effects, such as tall structures and those with heavy gravity loads.

4.4 Location of Specimen Period on Response Spectrum

The location of the fundamental period of the specimen on the response spectrum, as expressed for pulses by the ratio $T_{specimen}/T_{pulse}$, of the specimen fundamental period $T_{specimen}$ and the pulse period T_{pulse} influences the severity of the effects of softening-induced strength loss. A low ratio (between approximately 0.3 and 1) leads to increases in drift over the ductile baseline case for the same amount of strength loss due to deformation softening. This trend is apparent in Figure 10, in which analytical results show that deformation softening causes significant amplification of the peak interstory drift response in the short and intermediate period range when compared to elastic and ductile baseline cases.

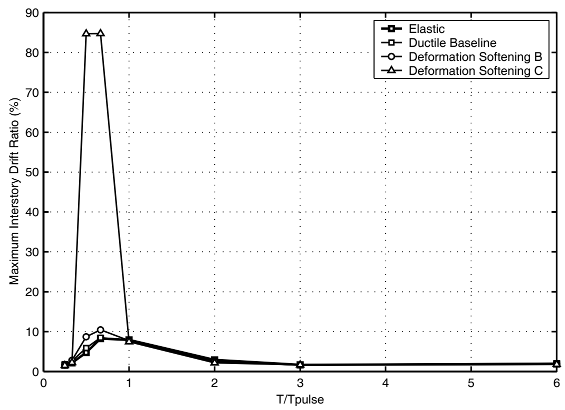

Figure 10. Shock spectra for deformation softening, ideally ductile, and elastic cases

5. CONCLUSIONS AND RECOMMENDATIONS

The effects of connection deformation softening on frame behavior depend on several factors. These factors include the amount of negative post-yield stiffness, the number of deteriorating connections, the excitation amplitude, and the specimen's position on the response spectrum. Both displacement and force response quantities were found to be sensitive to the combination of the negative post-yield tangent stiffness ratio and the number of deteriorating connections. Specifically, in the case where all connections deteriorated with the same negative post-yield stiffness, the response was very sensitive to the post-yield stiffness ratio. A combination of a sufficiently severe pulse excitation and a large negative post-yield stiffness ratio in all connections was observed to cause collapse of the experimental specimen. When only two of the four connections deteriorated, the response was not sensitive to the post-yield stiffness ratio and no collapses of the experimental specimen occurred. Further analyses indicate that the negative post-yield stiffness ratio necessary for collapse varies with the excitation amplitude. These analyses also show that a negative slope in the connection hysteresis exacerbates the effects of P-delta at large deformations. Future research should examine full-scale moment frame structures with connections exhibiting negative post-yield stiffness. Researchers should pay particular attention to structures that are more susceptible to P-delta effects, such as taller structures and those with heavy gravity loads. The authors anticipate that the presence of negative post-yield stiffness in such structures will have significant adverse effects on system performance at much lower drift levels than observed for the experimental specimen used in this research.

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