HYBRID MOMENT RESISTING STEEL FRAMES

Finley A. Charney[1] and Ozgur Atlayan[2]

[1] *Associate Professor, Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061, USA*
[2] *Graduate Student, Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061, USA*
Email: fcharney@vt.edu

ABSTRACT:

A new type of moment resisting steel frame, called a Hybrid Moment Resisting Frame, is described. Unlike a typical moment frame, where all member sizes and connection details fit a specific set of rules (e.g. for a special moment frame), the Hybrid Frame contains members and connections with a variety of detailing rules, including those typically associated with ordinary (OMF), intermediate (IMF), and special moment frames (SMF). Elements that have special detailing are designed to yield at force levels well below the design basis earthquake, and thereby provide some inelastic energy dissipation that helps to control dynamic amplification. Elements with ordinary detailing are designed to remain elastic during the design basis earthquake, and to provide enough positive stiffness to counteract P-delta effects. The resulting system is expected to perform better than the traditional special moment frame, and to be more economical than the special moment frame because a limited number of elements and connections have special detailing. The behavior of the system is demonstrated through incremental nonlinear dynamic response history analysis.

KEYWORDS: Seismic Design, Moment Resisting Frames, Structural Steel

1. INTRODUCTION

The current specifications for seismic resistant design (ASCE, 2006; AISC, 2005a; AISC, 2005b) require that special detailing be used in moment resisting frame systems that are to be constructed in high seismic hazard regions. This detailing requires the use of designated flexural yielding regions with limited width-to-thickness ratios, highly ductile pre-qualified connection types, limited panel zone yielding, and adherence to a strong-column weak-beam design philosophy. The structure must be designed such that first significant yield occurs at lateral force levels that at or above the Design Basis Earthquake (DBE) forces. The sequencing of plastic hinging is usually not explicitly designed, and hence, there is no guarantee that the slope of the structure's force-deformation response (pushover curve), including P-Delta effects, is continuously positive up to the maximum expected drift. This is a critical design issue because it is much more likely that dynamic instability will occur when the post-yield stiffness is negative (Gupta and Krawinkler, 2000). This fact has led to a significant revision in the 2003 NEHRP Provisions (FEMA, 2004) where it is required that the pushover curve be continuously positive up to 1.5 times the target displacement if the stability ratio, based on initial elastic stiffness and on design level gravity loads, exceeds 0.10. Another consequence of not explicitly designing the hinging sequence is that the expected over-strength, which is implicitly included in the system's Response Modification Coefficient, *R*, is not guaranteed. Indeed, there is nothing in the current design provisions that prevents a designer from developing a system for which a nonlinear static pushover analysis indicates that all of the hinges form nearly simultaneously.

In a Hybrid Moment Resisting Frame (HMRF), the hinging sequence is explicitly designed to assure a continuously positive post-yield pushover response. The HMRF shares many of the features of the Special Moment Resisting Frame (SMRF), with the following exceptions:

1) The yielding sequence is set such that the first plastic hinges form at load levels well below the design basis earthquake, and the last hinges form at load levels consistent with the maximum considered earthquake. The inelastic energy dissipation provided through early yielding is expected to improve the performance of the structure to earthquakes of intensity less than the design basis earthquake. The near-elastic response of the late-forming hinges is intended to guarantee a positive pushover response.

2) The detailing for the lateral load resisting components and their connections depends on the level of inelastic rotation that is expected in the various plastic hinges. The hinges that form first have the highest ductility demand, and are detailed according to the rules for special moment frames. It is noted that these hinges may have ductility demands that exceed those expected from traditional SMRF designs. The hinges that form last have the lowest ductility demand, and are detailed according to the rules for intermediate or ordinary moment frames.

The Hybrid Frame concept may be used for any structural system, such as concentrically braced frames, or buckling restrained braced frames. The concept of Hybrid Buckling Restrained Frames is particularly attractive because of the ability to tightly control the inelastic behavior of the yielding elements. The advantages of Hybrid Frames will be demonstrated through two examples. The first example is of a Hybrid Braced Frame, and is used only to demonstrate the concepts and to introduce some of the features used in the analysis. The second example is of a 9-story steel moment resisting frame.

2. DEMONSTRATION OF CONCEPTS: A HYBRID BRACED FRAME

In this demonstration, a simple one-story braced frame is analyzed. This fictitious frame, shown in Figure 1, is intended to have the dynamic characteristics of a 15 story building, with a first mode period of vibration of 2.0 seconds. Two different versions of the frame are presented. The first frame, called the "Normal" frame, has six identical diagonal braces, each with an axial strength of 141 kips. The second frame, called the "Hybrid" frame has bracing bars of the following strengths: bar 1 = 47 kips, bar 2 = 94 kips, bars 3 and 4 = 141 kips, bar 5 = 188 kips and bar 6 = 235 kips. The lateral strength of the structure, exclusive of P-Delta effects, is 600 kips. The axial stiffness of each of the bars, whether in the Normal or Hybrid Frame is 68.9 kips per inch. The initial lateral stiffness of each frame is 207 kips/inch. It was assumed that the bars were elastic-plastic, without strain-hardening.

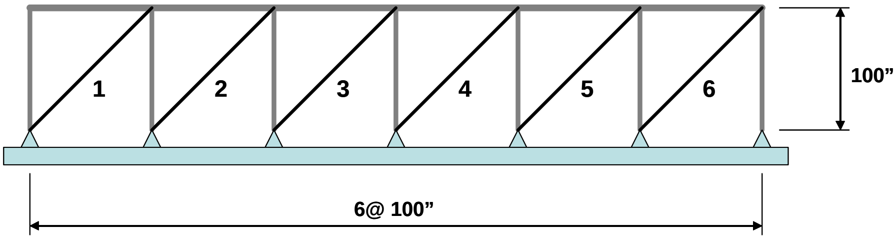
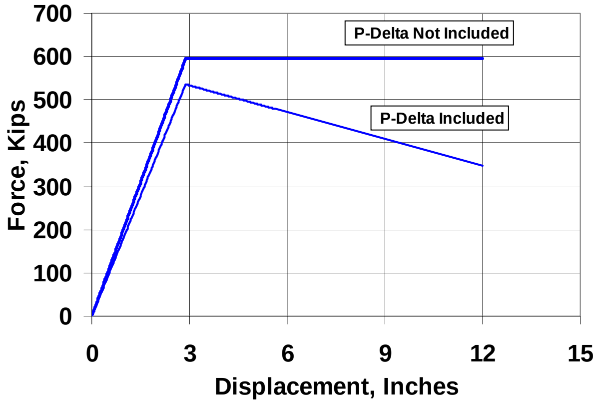


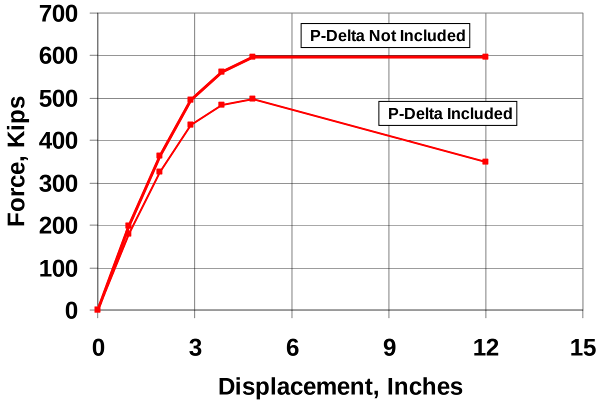
Figure 1 - A Simple Braced Frame

Nonlinear static pushover plots of the Normal and Hybrid frames are shown in Figs. 2(a) and 2(b), respectively. Response curves with and without P-Delta effects are shown. Where included, the P-Delta analysis emulates a structure with an average story stability ratio of 0.10.

To investigate the dynamic behavior the Normal and Hybrid structures, with and without P-Delta effects included, were subjected to the El Centro recording of the 1940 Imperial Valley ground motion, with a peak ground acceleration of 0.35g. For each case, the structure was repeatedly subjected to this ground motion, with each analysis using an incrementally larger ground motion multiplier. The multipliers ranged from 0.2 to 2.0, in increments of 0.2. For this example, it is assumed that a multiplier of 1.0 corresponds to the Design Basis Earthquake (DBE) and the factor of 1.5 corresponds to the Maximum Considered Earthquake (MCE).



(a) Normal Frame



(b) Hybrid Frame

Figure 2 - Nonlinear Static Pushover Curves for Braced Frame Structure

Analysis was run using NONLIN-Pro (Charney and Barngrover, 2006), which uses the Drain 2D-X (Prakash et al., 1993) analysis engine. All analyses were run with an inherent damping ratio of approximately 0.02. One set of analyses was run without P-Delta effects, and the other with P-Delta effects. When P-Delta effects were considered, both the Normal and Hybrid structures were dynamically unstable when the ground motion multiplier exceeded 1.5.

Plots of the results for the models without P-Delta effects are shown in Figures 3(a) through 3(d). Figure 3(a) plots the ground motion multiplier on the vertical axis and the computed roof displacement on the horizontal axis. The displacements appear to be similar for the two systems, except that it is noted that the Hybrid frame displacements are about 12 to 15% less than the Normal frame displacements for the first two increments of loading. For all ground motion levels less than or equal to the MCE, the residual inelastic deformations Fig. 3(c), are significantly lower for the Hybrid frame, when compared to the Normal frame. (Residual deformations are the permanent lateral deformations that remain in the structure after ground shaking has ceased.) At the ground motion intensity level of 1.8, however, the residual deformations in the Hybrid frame exceed those in the Normal frame. The base shears for the Hybrid frame, shown in Fig. 3(b) are also lower than those for the Normal frame for the first two increments of ground motion intensity.

Ductility demands for Bar 1, Bar 6, and for the average of all bars are presented in Figure 3(d). For the Hybrid frame, Bar 1 is the weaker bar, and as expected, the ductility demand is the highest. At the DBE level (multiplier 1.0), the ductility demand for Bar 1 is 6.61. At the same intensity, the ductility demand for Bar 6 is only 1.32, and the average ductility demand for all Hybrid bars is 2.88. For the Normal frame, the ductility demand for all bars is the same at each intensity level, and is 2.15 at the multiplier of 1.0.

It appears from the results that the Hybrid frame is performing as expected. Displacements at low level ground motions are reduced due to the early yielding and associated hysteretic behavior of Bars 1 and 2. Delayed yielding of the stronger bars provides a component of elastic stiffness that controls residual deformations.

When P-Delta effects are included, the performance of the Hybrid frame is further improved when compared to the Normal frame. This is illustrated in Figures 4(a) through 4(d), where it may be seen that the total displacements, Fig. 4(a), are significantly less in the Hybrid frame at all ground motion levels up to the DBE. This improved performance is due to the significant reduction in residual deformations, shown in Fig. 4(c). As mentioned earlier both the Hybrid and Normal frames displayed dynamic instability when the ground motion multiplier exceeded 1.5. This is due to the negative stiffness of the pushover curves (see Fig. 2) at larger displacements.

It is interesting to note from Fig. 4(b) that at ground motion multipliers between 0.6 through 1.0, the base shears for the Hybrid frame are somewhat greater than for the normal frame. This is not a disadvantage for the Hybrid frame, because the lower base shears for the Normal frame are associated with P-Delta related strength loss.

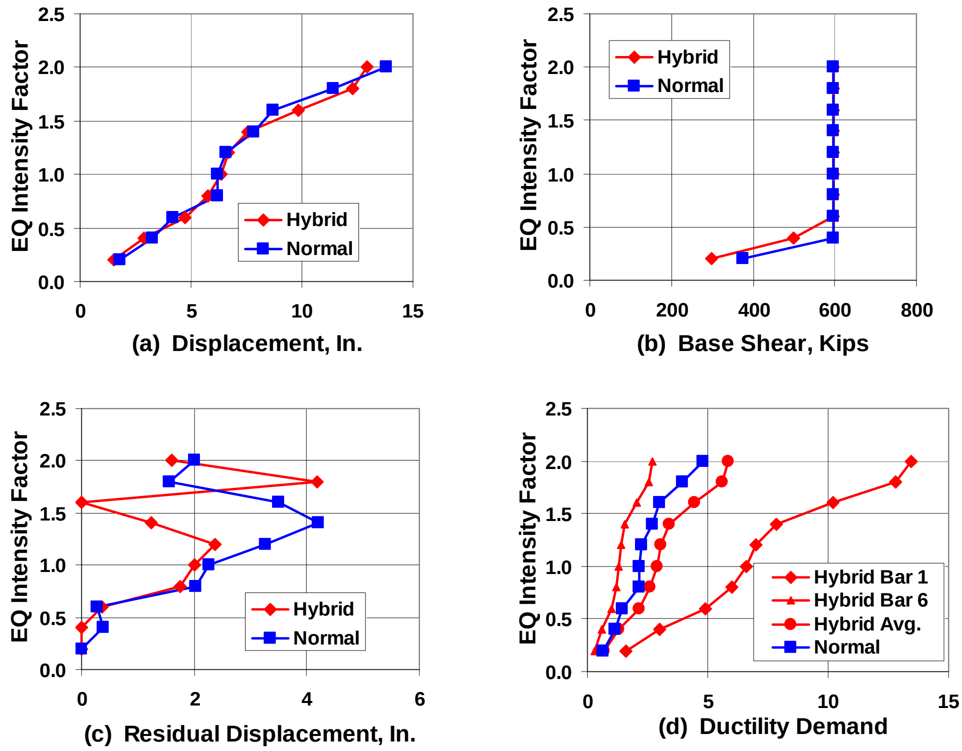


Figure 3 - Results of Frame Analysis Without P-Delta Analysis

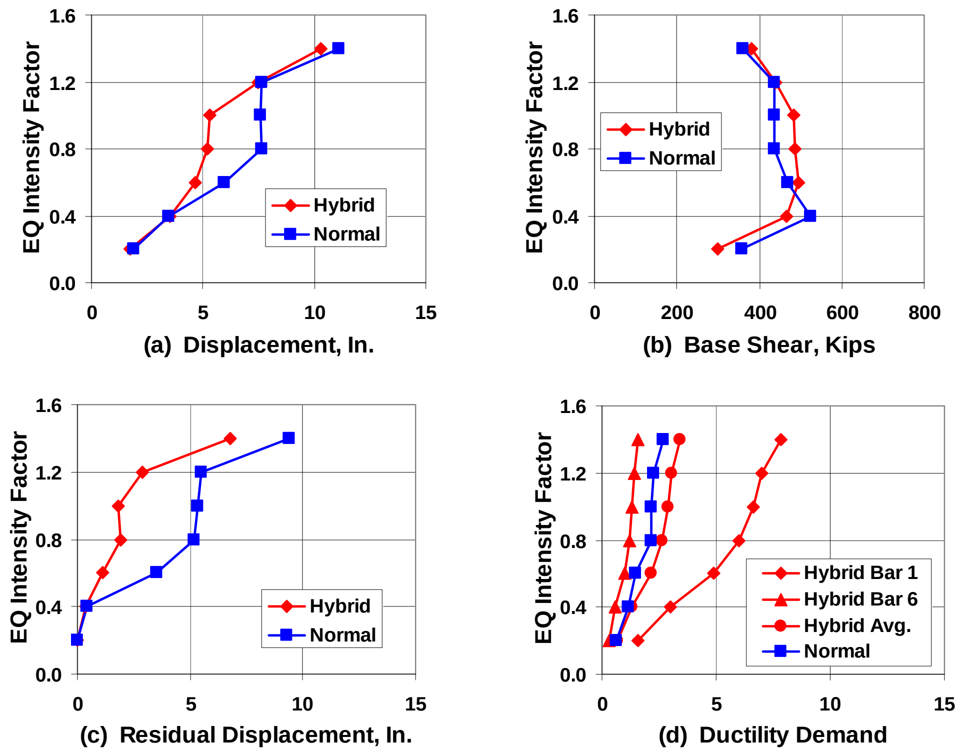


Figure 4 - Results of Frame Analysis With P-Delta Analysis

3. ANALYSIS OF A HYBRID MOMENT RESISTING FRAME (Preliminary Results)

The Hybrid Moment Frame concept is demonstrated by the analysis of a five-bay nine-story frame building, located near Seattle, Washington. The geometry of this building is identical to that studied in the SAC Steel Project (FEMA, 2000). The ASCE 7 design parameters used for the design are summarized in Table 1. Four different Hybrid frame configurations were used in this study. Figure 5 shows the member sizes used for different Hybrid frame combinations. (Member sizes for the girders are shown above each girder, with Combination 1 at the bottom and Combination 4 at the top.) Combination 1 is a Normal frame design without any change in the plastic hinge capacities throughout the story. For this design the response reduction factor R, was taken as 6, and the deflection amplification factor, C_d, was taken as 5. The two exterior girders of the Hybrid Frame (bays 1 and 5) were designed as special moment frames (SMF), the two interior girders (bays 2 and 4) were designed as intermediate moment frames (IMF) and the middle girder (bay 3) was designed as an ordinary moment frame (OMF). After the sections of the 1st hybrid combination (the Normal frame) were found, the plastic capacities were changed throughout the story. The plastic capacities of the exterior girders were decreased by 25%, 37.5% and 50% for the 2nd, 3rd and 4th hybrid frame combinations. Since the main idea of the Hybrid frame is to keep the total strength of the story the same, the plastic capacity of the middle girder was increased by 50%, 75% and 100%. The bay 2 and bay 4 girder capacities were kept the same for all combinations. In summary, as the combination number gets bigger, the frame becomes more hybrid with a greater variation in beam sizes across the width at each story. The column sections were kept the same for all the combinations but the panel zone doubler plate thicknesses were changed as necessary. Reduced beam sections were used for all the girders except for the girder in the middle bay, which was designed according to the rules for an OMF. The strong column - weak beam requirement was satisfied at the joints of the columns on column lines 1, 2, 5, and 6.

Table 1 - *ASCE 7-05* Design Parameters for Hybrid Frame

Design Parameter	Value
0.2 second spectral acceleration S_s	1.25 g
1.0 second spectral acceleration S_1	0.5 g
Site Class	D
0.2 second design acceleration S_{ds}	0.83 g
1.0 second design acceleration S_{d1}	0.5 g
Seismic Use Group	II
Importance Factor	1.0
Seismic Design Category	D
Effective Seismic Weight W	10,500 kips

All structural analysis was conducted using Perform-3D (CSI, 2006), using a planar model consisting of one of the two perimeter frames that are parallel to the design ground motion. Panel zones were explicitly represented by use of Krawinkler's model (Charney and Marshall, 2006). P-Delta effects were included in all analysis, using a special linear "ghost frame" which captures the entire gravity load tributary to the leaning columns. The inherent damping was determined by setting the critical damping ratio to 2% at the natural period of the structure and at a period of 0.2 sec as it was done in the SAC Report (FEMA, 2000). Two types of analysis were performed for each frame; nonlinear static pushover analysis (NSP) and incremental dynamic analysis (IDA). Pushover curves for the four different Hybrid Frames are shown in Figure 6.

Note that the point of the first significant yield and the point at which the post-yield curve becomes negative are shown on the figure. As expected, combination 4 starts yielding first, and combination 1 yields at last. The more reduction in the plastic capacity of the exterior bays, the earlier the structure starts yielding. In addition, the negative post yield stiffness of the pushover curves is reached later as the frames become more hybrid.

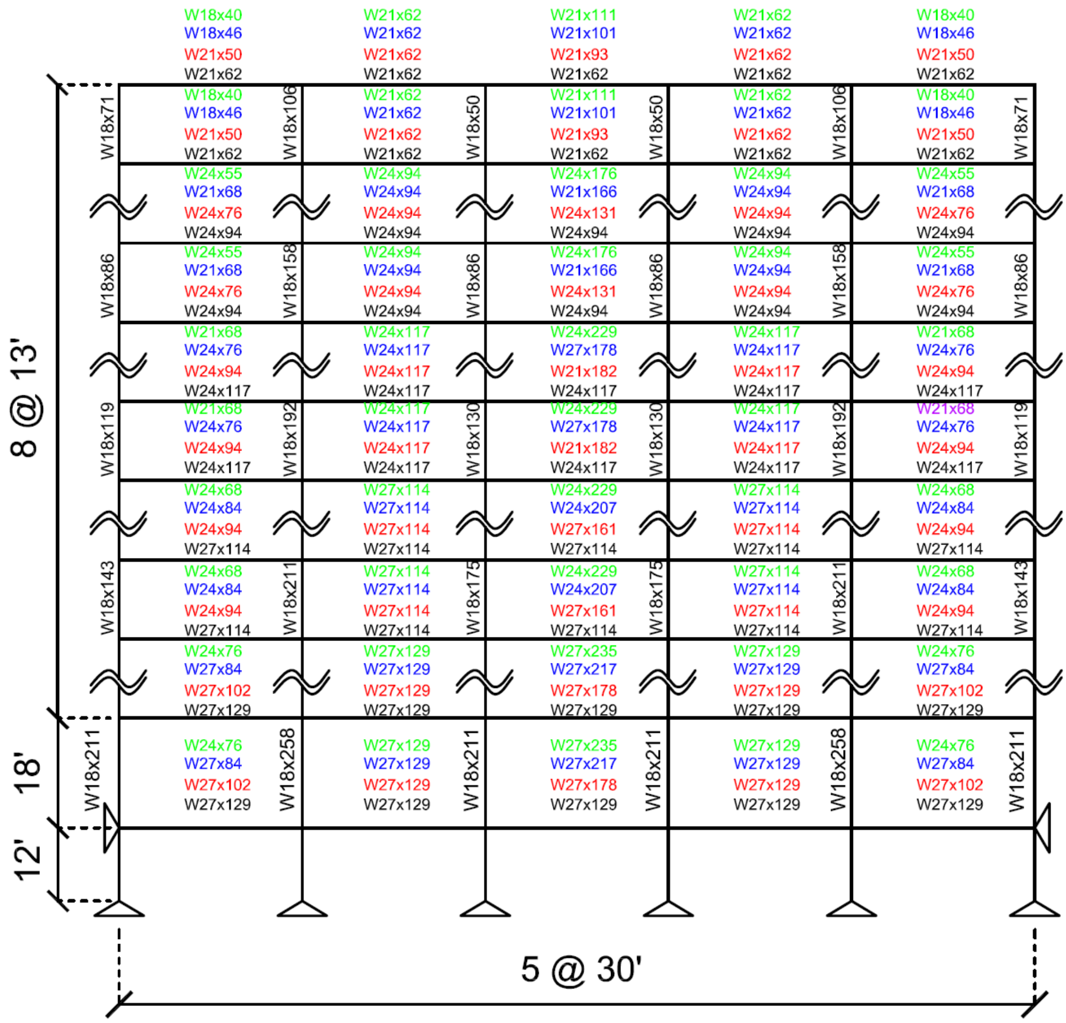


Figure 5 - Member Sizes Used for Hybrid Frames 1 to 4 (bottom to top)

In this study, incremental dynamic analysis (Vamvatsikos, 2002) was conducted for the structure subjected to ten different earthquake records, and at intensities of 0.2 to 2.0 times the ground motion scaled to match the design basis earthquake. The ground motions were scaled to match the ASCE-7 spectrum at the structure's fundamental period. This scaling procedure is recommended for IDA analysis by Shome and Cornell (1998). It is noted that the ground motions used in the analysis were the same as those used in the original SAC research (FEMA, 2000). Only a very brief summary of the results of the analysis is reported herein. See Atlayan (2008) for a detailed description of the analysis, and a much broader presentation of the results.

Figures 7 and 8 illustrate the roof displacement response histories of Hybrid frames subjected to Miyagi Oki (1978) and Valpariso (1985) earthquakes with scale factors of 2.0 and 1.8 times the anchored design spectrum scaling, respectively. These two earthquakes are the most severe ones out of all the earthquakes used in this study. As can be seen from Figure 7, the 1st, 2nd and 3rd Hybrid frame combinations reach dynamic instability whereas the 4th combination, which is the most hybrid, resists the collapse with 60 in. of residual displacement at the roof level. All the Hybrid frame combinations collapse when they are subjected to Valpariso earthquake with 1.8 IDA scaling (see Figure 8). However, as the frames become more hybrid, they resist the collapse more, i.e. collapses occur at a later time.

According to the results of IDA analysis, Hybrid frames always give better results when the structures are subjected to severe earthquakes, and almost always, as the frame gets more hybrid, the results becomes better. This structural behavior can be explained with the effect of the relatively late occurrence of negative post yield stiffness in Hybrid frames.

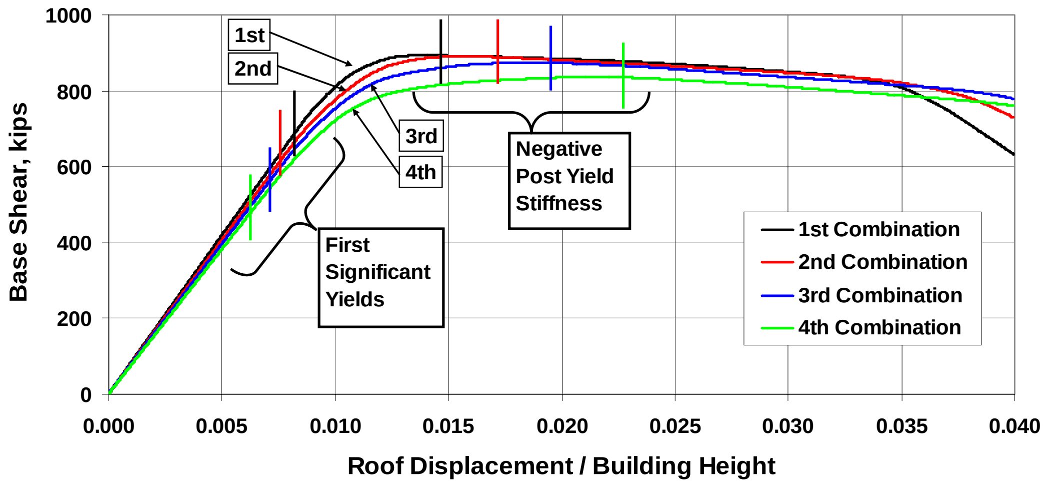


Figure 6 - Static Pushover Curves for Hybrid Frames

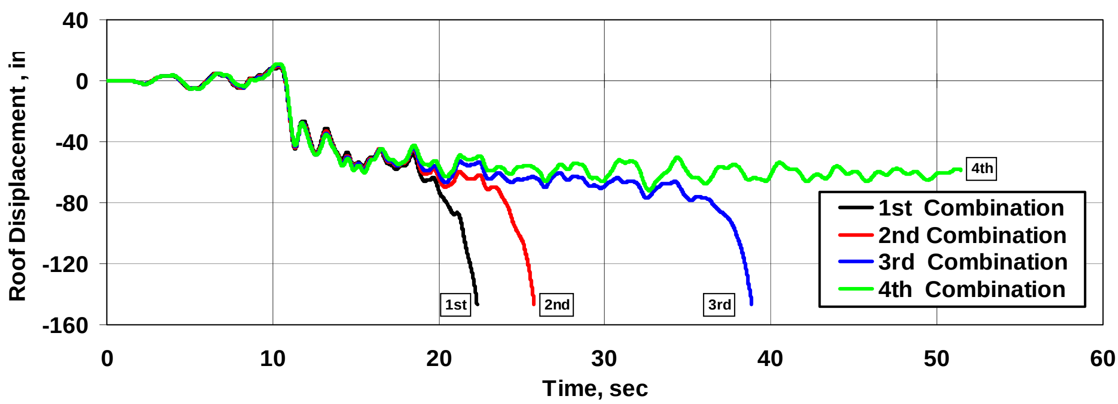


Figure 7 - Roof Displacement Response History of Hybrid Frames subject to Miyagi Oki Earthquake with scale of 2.0 times the anchored design spectrum scale.

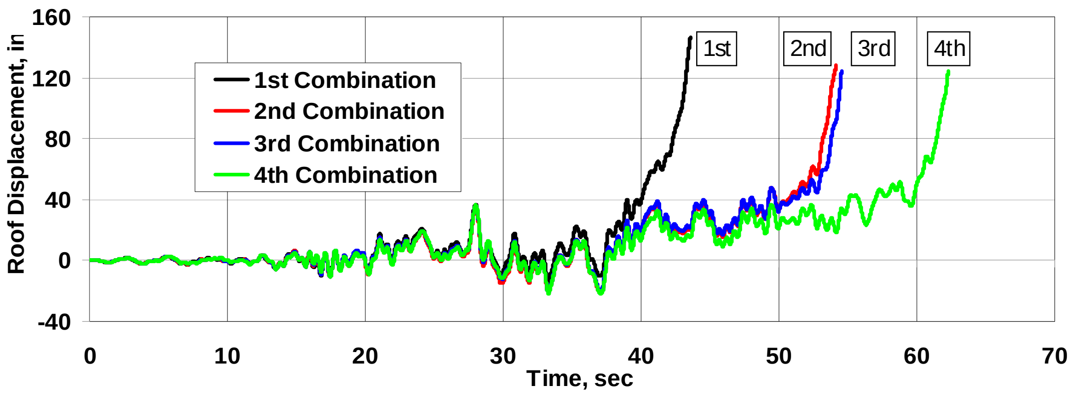


Figure 8 - Roof Displacement Response History of Hybrid Frames subject to Valpariso Earthquake with scale of 1.8 times the anchored design spectrum scale.

4. SUMMARY and CONCLUSIONS

While the work reported in this paper is preliminary, it appears that there are significant benefits associated with the concept of Hybrid frames. By carefully controlling the sequence of yielding, there is a clear indication of improvement in response at all levels of ground shaking, particularly at higher levels where dynamic instability may be more prevalent. At lower levels of shaking, the improvement is less significant, although there is a trend towards reduced displacements and base shears. This behavior is associated with the energy dissipation provided by early yielding of the low-strength plastic hinges.

For the frames studied, there is a significant increase in ductility demand, compared to traditional special moment frames, for those elements and connections that are expected to yield early. Although it is expected that traditional special moment frame detailing will suffice for these locations, additional research needs to be done to determine how much ductility can actually be provided by such connections. It may be necessary to develop special connection details for these areas. The use of special low-strength steels should also be investigated.

Additionally, the Hybrid frames described herein were designed on an ad-hoc basis, as no specific rules have been established for assigning the sequence of yielding. It is expected that improved performance can be obtained if the sequence of hinging is more formally optimized. The use of an energy based procedure is being explored for use in the development of an optimum hinging sequence.

Finally, additional work needs to be done to determine if significant economy is obtained by the Hybrid frames. Such economy would be expected even if the performance of the hybrid frames was equivalent to the normal frames. This advantage in economy is due to the reduction in the number of special moment connections in the structure.

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