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SIMPLIFIED MODELING TECHNIQUES FOR A PROPOSED RETROFIT SYSTEM USING HIGH-PERFORMANCE FIBER-REINFORCED CEMENTITIOUS COMPOSITES

Kyle S. DOUGLAS[1], Sarah L. BILLINGTON[2], and Keith E. KESNER[3]

SUMMARY

The focus of this work is the development of a simplified finite element model for large scale structural analysis of a proposed retrofit system. The retrofit system, which is currently being investigated for application to steel frame structures, is comprised of a series of ductile fiber-reinforced cementitious composite infill panels. In this paper, simple finite element models using beam elements are presented for simulating the hysteretic behavior of individual panels and compared to experimental results. An investigation of various modeling strategies for a single steel frame bay with the retrofit system in place is also presented. It was found that there is a mesh dependency for the simple beam models for this application and that with incorporation of slip at the panel base connection, the simple models could predict the initial stiffness of the panels with reasonable accuracy. However without modeling bond-slip and reinforcement fracture, the peak strength and pinching of the hysteresis could not be simulated with much accuracy. Modeling a full bay with a plane stress continuum approach and with a 2D beam element approach showed minor differences in predicted response.

INTRODUCTION

In light of the lessons learned from past earthquakes and the advances in earthquake engineering, critical facilities such as hospitals are in need of conforming to current earthquake resistant design specifications. For many such facilities, retrofitting the structure poses a considerable problem in that the facility should be allowed to function while the retrofit strategy is being implemented. This need for continuing functionality motivates the necessity for a flexible and portable retrofit strategy that can be put in place with minimal disturbance to the facility.

This paper discusses a proposed retrofit strategy for steel framed structures that can accommodate floor plans and secondary system layouts of the existing facility and possibly provide minimal disturbance to the function of the building during installation (Kesner [1]). The retrofit strategy is an infill panel system consisting of a series of precast panels that act as deep beams under lateral load within the frame. The

[1] PhD Candidate, Stanford University, Stanford, USA. Email: kyled@stanford.edu
[2] Clare Boothe Luce Assistant Professor, Stanford Univ., Stanford, USA. Email: billington@stanford.edu
[3] Instructor, Cornell University, Ithaca, USA. Email: kek11@cornell.edu

panels are composed of a high performance fiber-reinforced cementitious composite (HPFRCC) material that does not spall and exhibits fine multiple cracking leading to energy dissipation under cyclic loading.

Of particular interest in this work is the ability to simulate the behavior of a structure with the retrofit system in place. Reliable simulations not only provide information as to how well key structural elements will respond to seismic loads, but also allow us to predict interstory drifts and floor accelerations. This latter information can then be used to determine if important secondary systems, such as water and electrical systems, will be damaged during an earthquake.

In the following sections, the proposed retrofit system will be described along with a brief summary of HPFRCC materials. The paper will then focus on the simulation of the hysteretic behavior of the individual panels, using a set of experiments to calibrate the models. Finally, these panel models will be placed in a single steel-frame bay to study the behavior of a frame with the retrofit system in place.

PROPOSED RETROFIT SYSTEM

Infill frames have been researched extensively since the 1950's, with typical infill materials including concrete, masonry, and concrete masonry units (CMU). One of the first studies into the behavior of infill frames was Benjamin and Williams [2], who developed empirical methods for predicting the shear capacity and deflection of reinforced concrete frames with concrete infill panels. Holmes [3, 4] presented the concept of an "equivalent strut" in the infill panel to carry the lateral load, and this idea was further developed by Stafford Smith [5, 6]. Finally, Kahn and Hanson [7] compared the behavior of three types of infill systems for reinforced concrete frames. The first infill system consisted of a solid precast wall, the second system was a cast-in-place solid wall, and the third system was comprised of six precast panels spanning across the frame. In the latter system, the precast panels acted as a series of deep beams under lateral load.

The proposed retrofit system, which is shown for a single bay in Figure 1, is similar in concept to the precast panel system of Kahn and Hanson. The retrofit system is specifically designed for steel framed buildings, and consists of a series of precast, fiber-reinforced concrete panels that act as deep beams when resisting lateral load. The panels are connected to each other using steel tabs and pretensioned bolts (Figure 2(a)). Each pair of panels is then connected to the steel frame with angles and pretensioned bolts (Figure 2(b)).

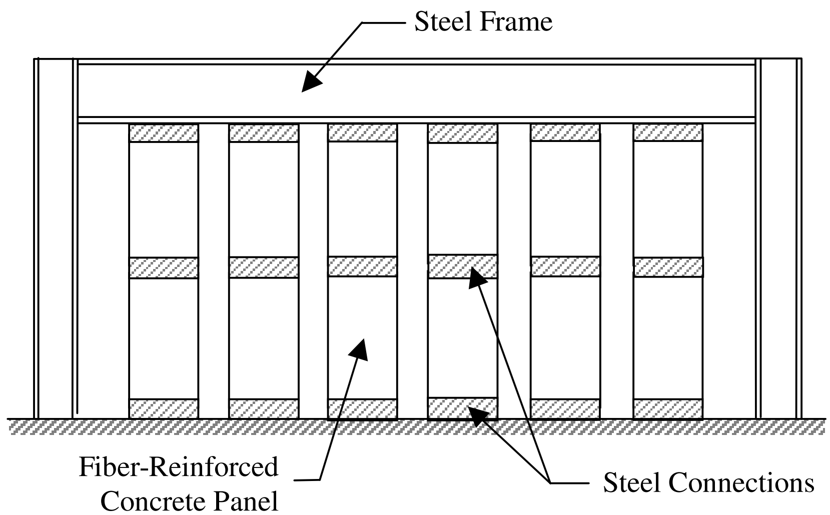


Figure 1: Proposed retrofit system.

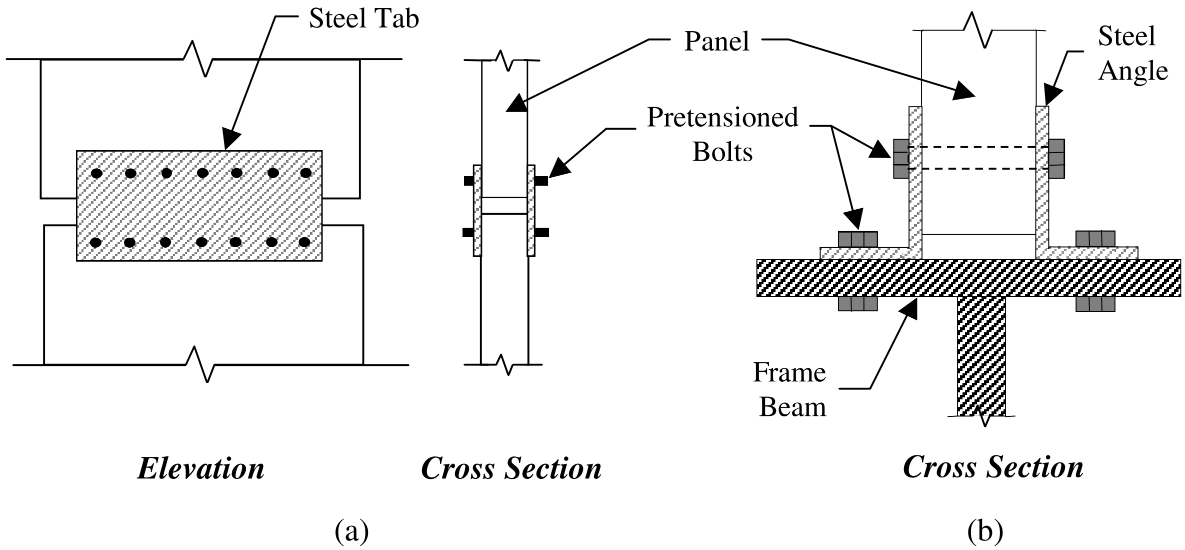


Figure 2: Connection details for panel-to-panel connections (a) and panel-to-frame connections (b).

The panels are composed of HPFRCC. As discussed in the following section, the properties of HPFRCC materials give them an inherent ability to dissipate energy under cyclic loads. The HPFRCC panels may be rectangular or tapered (Figure 3). Tapered panels may be a more efficient load-carrying option since the geometry follows the distribution of moment within the panels. As shown in Figure 3, each panel is reinforced with a combination of welded wire fabric (WWF) and a 9.5mm-diameter bar around the perimeter of the panel.

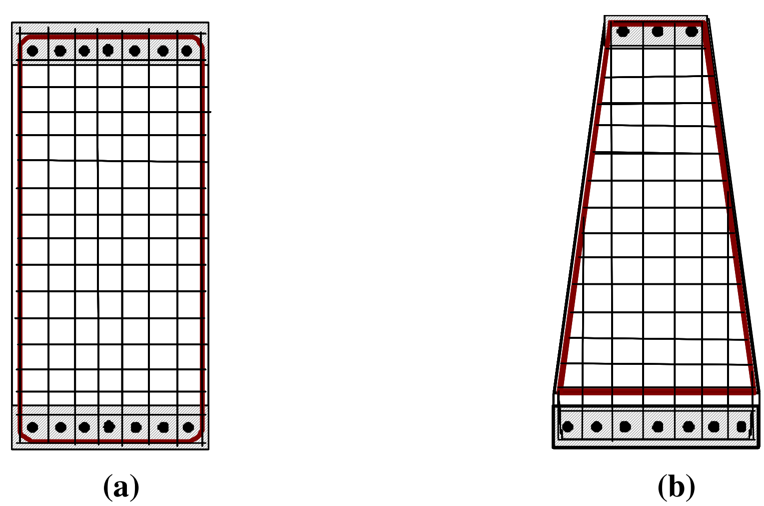


Figure 3: Panel geometry and reinforcement for rectangular panels (a) and tapered panels (b).

The main advantage of this retrofit system is that it is a portable and flexible system. Since the infill consists of a series of panels instead of a full wall, the system can accommodate floor plans and secondary systems that require access through the bay by adjusting the location of each pair of panels. Depending on the layout of the facility, the individual panels may be moved into place and installed into specified bays with minimal disturbance to the function of the facility. Furthermore, damaged panels can be easily replaced by simply unbolting them from the frame.

Related research on the use of HPFRCC materials as infill panels has been conducted by Kabele et al. [8], Horii et al. [9], and Kanda et al. [10]. Kabele et al. and Horii et al. examined the behavior of HPFRCC infill panels through a simulation-based study. Kanda et al. studied the behavior of HPFRCC shear panels connected using pretensioned bolts. A more detailed discussion of this retrofit strategy is given by Kesner [1].

DUCTILE FIBER REINFORCED CEMENTITOUS COMPOSITES

The HPFRCC materials used in this study are comprised of a Portland cement-based mortar matrix that is reinforced with a 2% volume fraction of polymeric fibers. The mortar consists of fine silica sand (less than 0.3 mm in diameter), which represents the only aggregate in the composite.

In uniaxial tension, HPFRCC materials undergo steady-state cracking [11, 12], resulting in the formation of multiple cracks. The multiple cracking leads to a strain hardening-like response in tension (Figure 4), giving HPFRCC materials the ability to dissipate energy under repeated cycles of crack opening and closing. Furthermore, Kesner et al. [13] showed that reversed cyclic tension-compression loading does not limit the tensile strain capacity of HPFRCC materials, provided the compressive strength of the material is not exceeded. Thus, results from monotonic tensile and compression tests of HPFRCC materials can be used to provide input parameters (modulus of elasticity, peak stress, peak strain) for a cyclic material model provided that the compressive strength is not anticipated to be exceeded. The micromechanics of the strain hardening response in HPFRCC materials is well documented in the summary in Li [14] and by Li & Leung [12].

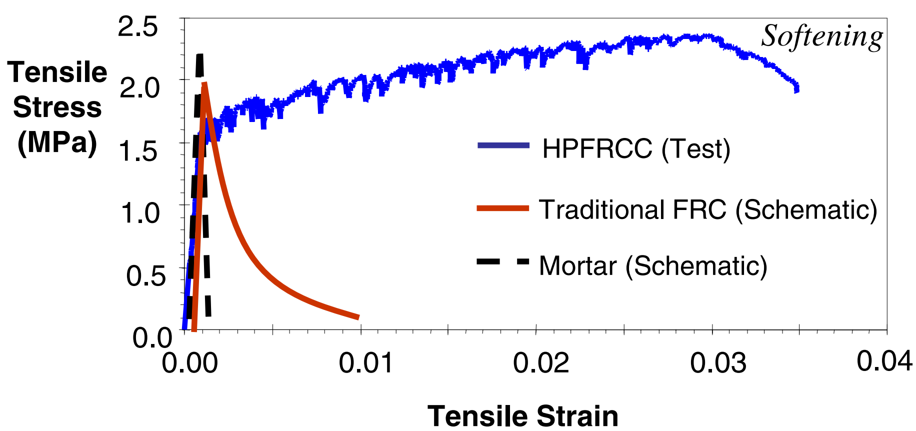


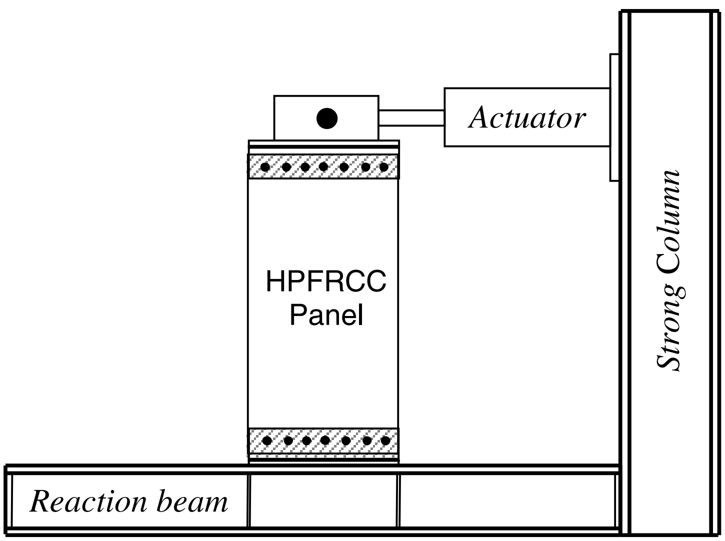
Figure 4: Uniaxial tensile response of HPFRCC materials.

SINGLE PANEL EXPERIMENTS

The purpose of the current study is to develop a simplified finite element model for large scale structural analysis of the proposed retrofit system. Such an analysis would include examining the behavior of a full scale steel frame building with the retrofit system in place. However, before a large scale analysis can be performed, it is critical to ensure that the behavior of the individual panels under lateral load can be simulated.

The basis for evaluating the panel simulations are a set of experiments performed by Kesner [1]. In these experiments, HPFRCC panels were cyclically loaded using the test set-up shown in Figure 5. Parameters that were varied included fiber type, panel geometry (rectangular and tapered), the inclusion of aggregate (silica sand), and the inclusion of the perimeter bar (see Figure 3). In addition, a concrete panel was tested and served as a control against which the performance of the HPFRCC panels could be evaluated.

Load vs. Drift results from two of Kesner's HPFRCC panels and the concrete panel are presented in Figure 6. Each of these panels had the same reinforcement layout. The only variable was the type of cement-based material used. Panel 3 used HPFRCC with Ultra High Molecular Weight Polyethylene (UHMWPE) fibers and Panel 4 used Polyvinyl Alcohol (PVA) fibers. Panel 5 used traditional concrete. As shown in Figure 6, the capacity of the HPFRCC panels is roughly 40% greater than that of the concrete panel, leading to a significant increase in energy dissipation. Degradation in the panel capacity after the peak load was reached was a result of cracking in the HPFRCC and concrete, bond slip and development failure, and fracture of the WWF.



(a)

(b)

Figure 5: Test set-up for cyclic lateral load experiments on single panels (a), and a panel specimen just prior to testing (b).

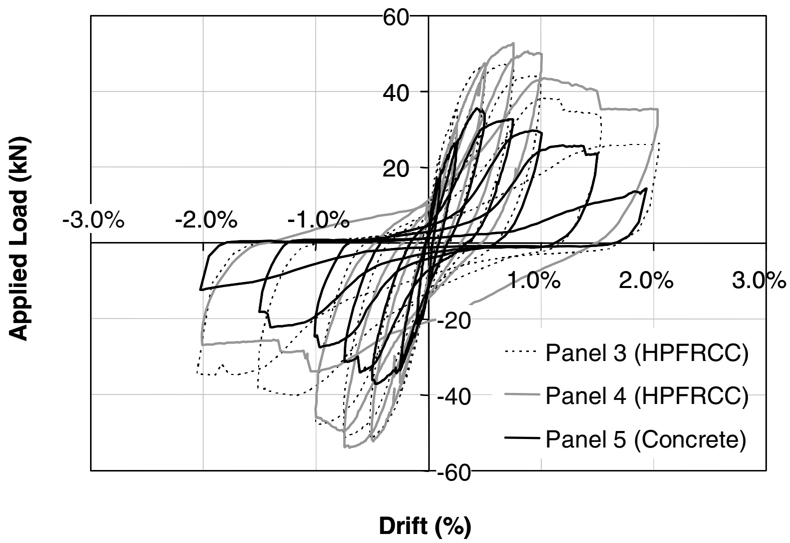


Figure 6: Hysteretic response of single panels under cyclic lateral loading up to 2% drift.

PANEL MODELS

Developing an acceptable model of the hysteretic lateral load behavior of the HPFRCC panels is the first step in working towards a large scale finite element analysis of the retrofit system. To reduce the computational cost of such an analysis, it is necessary to model the panels and the steel frames using beam elements. Once the panels models have been validated, an analysis may be performed on one bay of the steel framed structure with the panels in place. Finally, these bays may be built up to form a complete structure. This section presents a discussion on simplified panel models as compared with experimental results, while the next section focuses on modeling approaches for single-bay frame models.

Fixed Beam Panel Model

The behavior of the panels under cyclic lateral loads was first modeled using a fixed-end cantilever beam, as shown in Figure 7. A panel was modeled using a 3-noded beam element, with two integration points along the length and six along the width. The integration points along the width make the panels more flexible, prevent abrupt changes in stress during material degradation [15], and allow crack opening and closing in the panel to be monitored more effectively. Embedded reinforcement elements (shown as dashed lines in Figure 7) were used to model the WWF and perimeter bar in the panel. The embedded elements were assumed to have perfect bond with the HPFRCC and the concrete. All finite element analyses in this work were performed using displacement control.

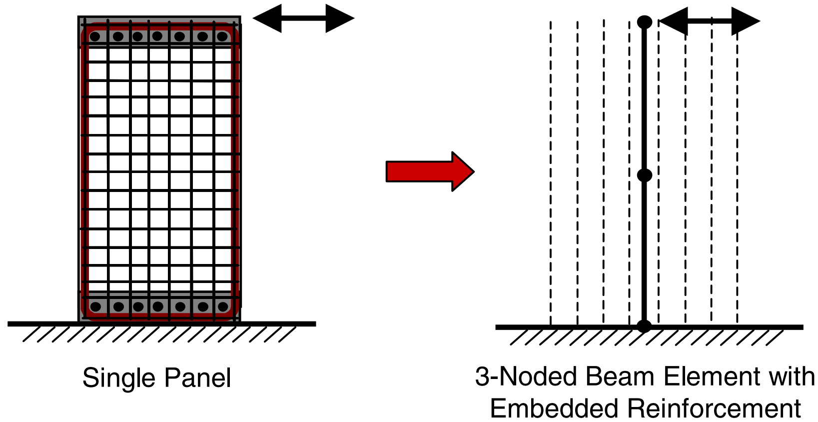


Figure 7: Modeling the panels as fixed beams.

A uniaxial total strain-based model was used for the HPFRCC. An idealized stress-strain relationship for the HPFRCC material is shown in Figure 8, where f_{crack} is the stress at first cracking, f_t is the tensile strength, and f'_c is the compressive strength. In this constitutive model, secant loading and unloading was used.

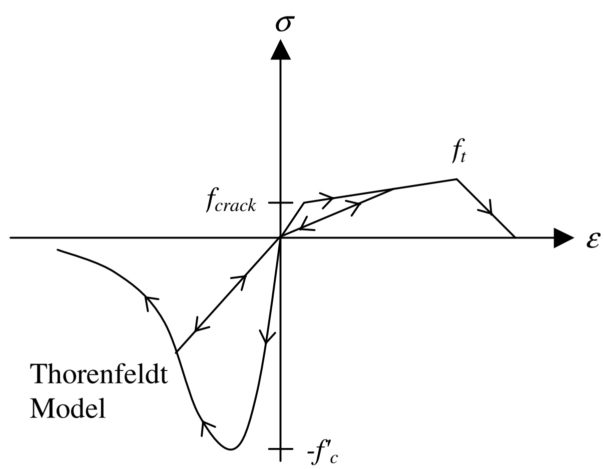


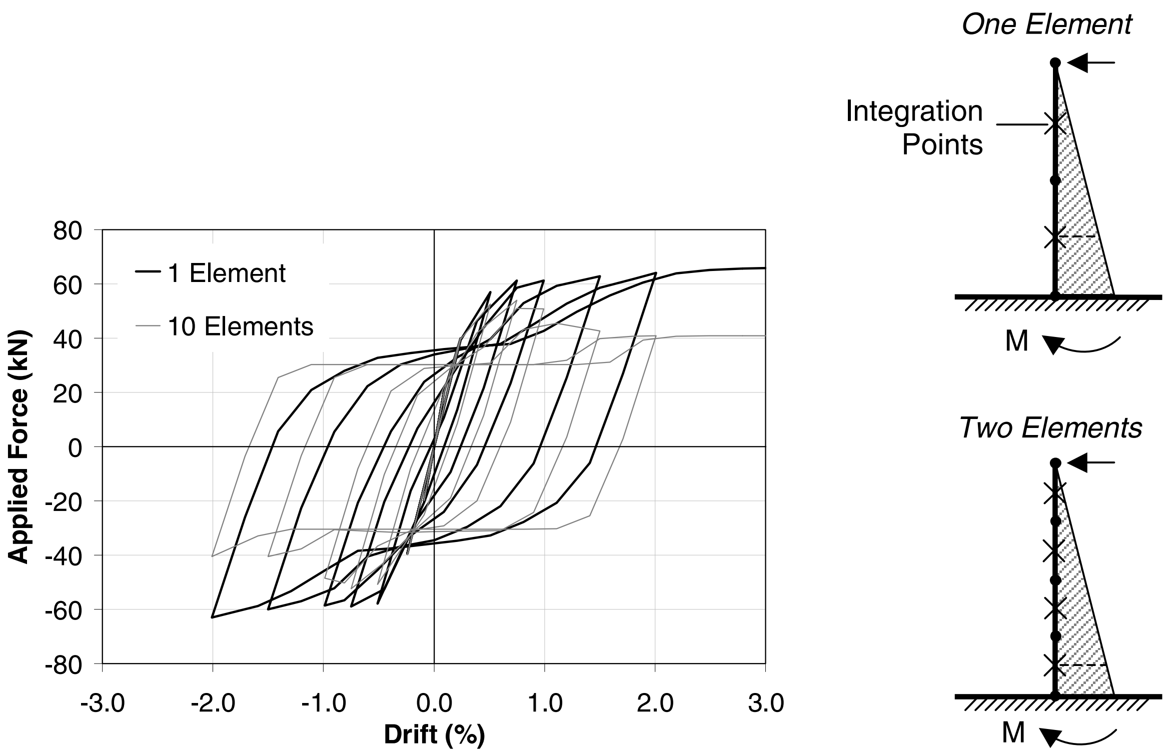
Figure 8: Idealized stress-strain relationship for the HPFRCC.

Parametric Study
Prior to examining the hysteretic response of the fixed beam panel model to lateral loading (Figure 7), a parametric study was conducted to determine the sensitivity of the model to the type of cracking implemented (rotating vs. fixed) and the number of beam elements used to make up the panel.

Two types of total strain, smeared cracking models were considered in this study: fixed cracking and rotating cracking (a good discussion of smeared cracking models is given by Rots [16]). However, for the fixed beam panel model, the hysteretic response of the panel was identical for the two models.

A variation in results was observed when the number of elements in the panel was varied. Figure 9(a) shows the hysteretic response of the panel using one and ten elements. The most striking difference in Figure 9(a) is the plateau of zero stiffness that occurs after unloading and prior to reloading for the ten-element model. This plateau represents a point in the loading history where the panel is fully cracked (i.e. cracks on the compression side of the panel are not yet closed and tension cracks are opening) and all of the reinforcement has yielded in compression and tension. Thus, the panel has zero stiffness. This phenomenon was present for models that used four or more beam elements.

This mesh sensitivity in Figure 9(a) may be explained by examining the moment diagram of the panel with for varying numbers of elements (Figure 9(b)). With the addition of a second element, the lowest integration point in the model moves closer to the base of the panel, where the moment and therefore stresses are higher. Consequently, this element will experience a greater degree of cracking and yielding in the reinforcement which is most significant when 4 or more elements are used.



(a) **(b)**

Figure 9: Mesh sensitivity in the panel model (a) resulting from increased element stresses (b).

Based on the results of the parametric study, the panels were modeled using a total strain rotating crack model and only one element. The decision to use one element was made to avoid the zero stiffness plateau that was shown in Figure 9(a), since this behavior will lead to an overestimation of the energy dissipation of the panel (compare Figure 9(a) for ten elements with Figure 6). It should be noted that using two elements per panel yields results that have negligible differences from those for one element. Thus, one element is a more desirable option since it will reduce the number of degrees of freedom in a large scale analysis.

Hysteretic Behavior
The hysteretic behavior of the fixed beam panel model is compared with the experimental response of Panel 4 (see Figure 6) in Figure 10. There are two shortcomings of the fixed beam panel model that are apparent. First, the simulated response is roughly 30% stiffer than the experimental response (Figure 10a). Second, the simulated peak lateral load capacity is 32% larger than the experimental capacity. Finally, the hysteresis loops in the simulation do not pinch upon unloading thus causing increased energy dissipation by the panels.

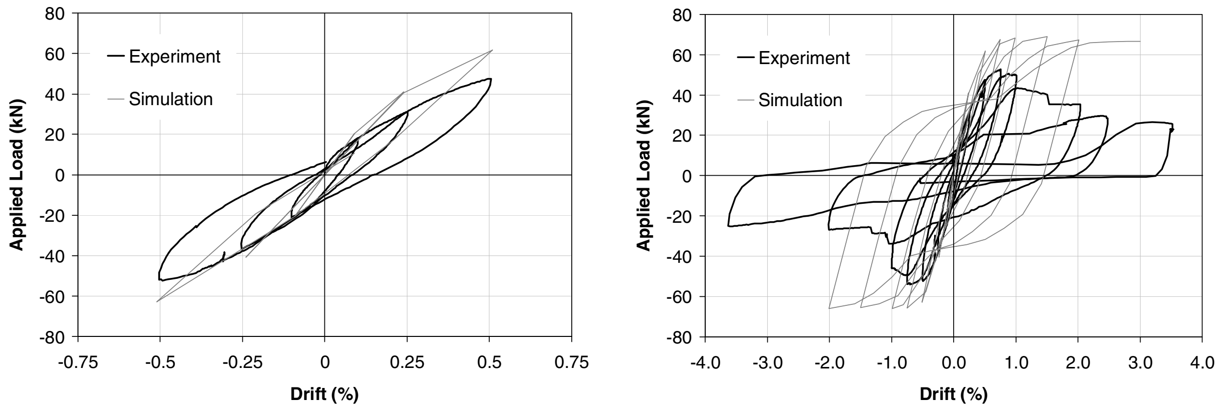
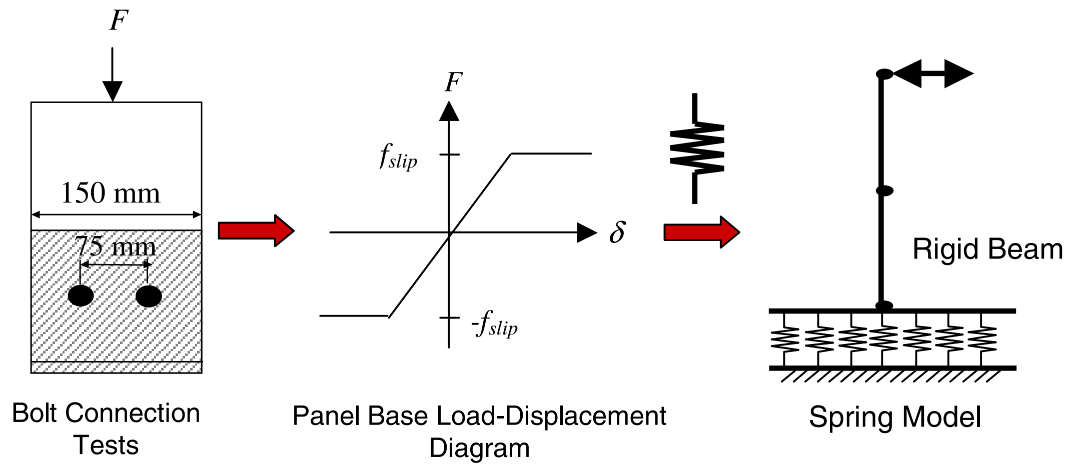


Figure 10: Hysteretic behavior for the fixed beam panel model in the initial cycles (a) and full response (b)

The high degree of pinching observed in the experimental results is attributed to bond-slip of the reinforcement as well as some rigid body rotation of the panel from slippage within the pretensioned bolted connection. As a first step, the slippage of the panel is modeled here to determine the extent of its contribution to simulating accurately the experimental response.

A Spring Model for the Panels
Under cyclic lateral loading the panels were observed to have slipped within the bolted connection region at the panel base [1]. This rigid body motion of the panels is undesirable because it could lead to the panels bearing on the bolts, which would reduce the capacity of the connection region [1]. Furthermore, rigid body motion reduces the energy dissipating potential of the panel in a given drift cycle and could lead to some degree of pinching. Therefore, the effects of panel slip were incorporated in our model.

Kesner [1] performed a set of experiments to characterize connection behavior including measuring the potential slip of the panel in the connection region. In these experiments, illustrated in Figure 11(a), a segment of the panel was loaded perpendicular to the line of the pretensioned bolts (see Figure 2(b) for a cross-section). The data from these experiments can be idealized as shown in Figure 11(b), where δ is the displacement of the *bottom* of the panel through the connection region (i.e. the slip of the panel). The load-slip relationship was linear up to a critical load, at which point the panel slips without further increase in load. This type of "elastic-plastic" relationship can be easily modeled using a spring element, which is shown in Figure 11(c) for the full panel. Note that the vertical spring elements are representing the slip of the panel at the horizontally oriented pre-tensioned bolts.

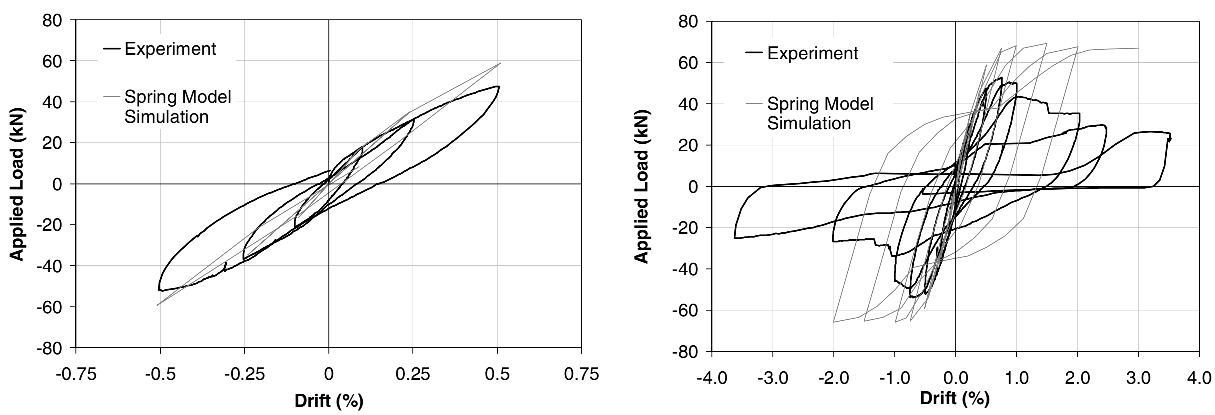


(a) (b) (c)

Figure 11: Development of a connection-slip model for the panels.

Seven pretensioned bolts were used in the connection regions of the panels during the single panel experiments (Figure 5(b)). Thus, seven spring elements were used to represent the load-slip behavior at each bolt location. A "rigid beam" element was used to connect the panel element to the springs and ensure that the rotation was rigid body rotation.

The hysteretic behavior of the panels with the slip springs compared to the experimental response is presented in Figure 12. A comparison of Figures 10 and 12 reveals that the addition of rigid body rotation to the panel reduces the initial stiffness of the panel to within 10% of the experimental stiffness (Figure 12 (a)) and adds a small amount of pinching to the hysteretic response (Figure 12(b)). The peak capacity of the panel remains similar, as expected.



(a) (b)

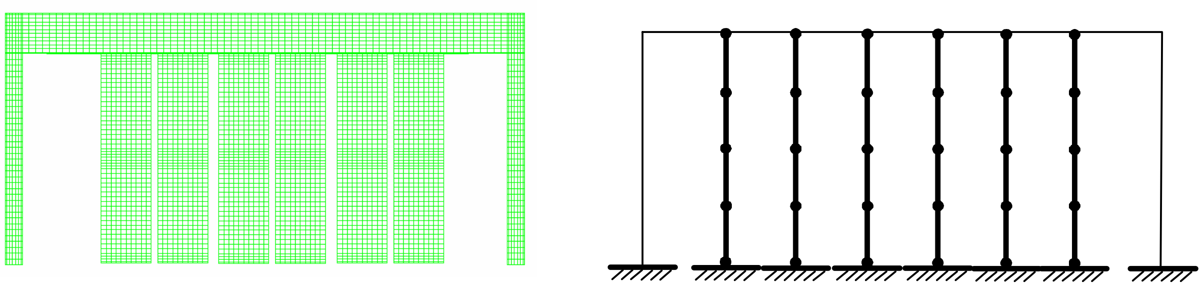
Figure 12: Hysteretic response of the panel when slip in the connection region is modeled: initial cycles (a) and full response (b).

While accounting for the slip of the panel in the connection region is important to capture the correct initial stiffness of the panels, the model falls short of providing an accurate overall simulated response. The increased capacity and energy dissipation simulated is attributed to the lack of bond-slip modeling in the reinforcement. Furthermore, all reinforcement was considered to be elastic-perfectly plastic with no fracture strain. Therefore these simulations would not be able to capture any strength degradation due to fracture of the reinforcement, as was observed in the WWF in several experiments [1]. While some of the pinching in hysteresis may be due to rigid body rotation of the panel as shown in Figure 12(b), the majority of the pinching appears to be caused by bond slip. Fiber element models are currently being considered to implement reinforcement fracture and bond slip in the panels.

SINGLE-BAY FRAME MODELS

To assess the effect of these panels as an infill retrofit system in steel frame structures, simulations on single bay frames were conducted. While the single panel models in the previous section could be evaluated against experimental results, there are to date no experimental results for infilled frames. As a first step to analyze the impact of the retrofit on a frame, two modeling approaches are considered; a plane stress continuum modeling approach and a 2D beam-element approach.

A plane stress nonlinear finite element analysis of a single bay with the retrofit system (Figure 13(a)) was performed by Kesner [1] for a cyclic lateral displacement applied to the top of the frame. The plane stress model consisted of 4-noded quadrilateral elements, and included elements for the steel tabs connecting the panels as well as the pretensioned bolts connecting the panels to the frame. The HPFRCC was modeled with a total strain-based model with smeared cracking. In the core of the connection regions the HPFRCC was assumed to remain elastic due to the confinement offered by the pretensioned bolts. The connection region elements were given a composite stiffness of the steel tabs and elastic HPFRCC. Embedded reinforcement elements, implying no bond-slip modeling, were used to model the WWF and perimeter bar in the panels.



(a) **(b)**

Figure 13: Single-bay finite element models with the retrofit system; plane stress finite element model (a) and beam element model without panel springs (b)

The results of the plane stress analysis are presented in Figure 14, along with the results of the same loading acting on a beam element model of the plane frame and the infilled frame. In the infilled beam model (Figure 13(b)), each panel is represented by one beam element (two elements through the height of the frame) as a result of the parametric study discussed earlier. The beams are modeled with fixed ends (i.e. no springs) for these simulations.

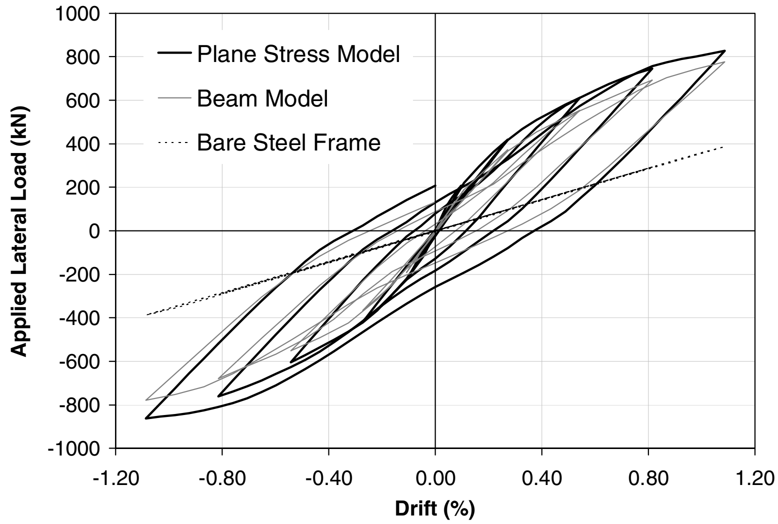


Figure 14: Hysteretic response of a single-bay steel frame with and without the retrofit system.

Based on these simulations, it is clear that the infill system will increase the strength, stiffness and energy dissipation capacity of a single bay frame.

In general, the two infilled models exhibit similar hysteretic behavior. The plane stress model has a slightly higher stiffness and less pinching than the beam element model. The difference in stiffness is attributed to the inclusion of the steel tabs, angles, pretensioned bolts, and elastic HPFRCC material in the connection region for the plane stress model. Since neither model includes bond slip, the lack of pinching in the plane stress model is also likely a result of the elastic HPFRCC in the connection regions.

It is interesting to note the proportion of load carried by the panels as the drift increases. The amount of lateral load carried by the panels as characterized by horizontal reactions at the base of the panels is shown in Figure 15 for the beam element model. Initially, the panels carry over 80% of the lateral load on the frame. However, after 1% drift has been reached, the panels are only carrying roughly 50% of the lateral load. In reality, this latter proportion will be lower since the panel models currently do not capture the degree of strength and stiffness degradation shown experimentally in the panels.

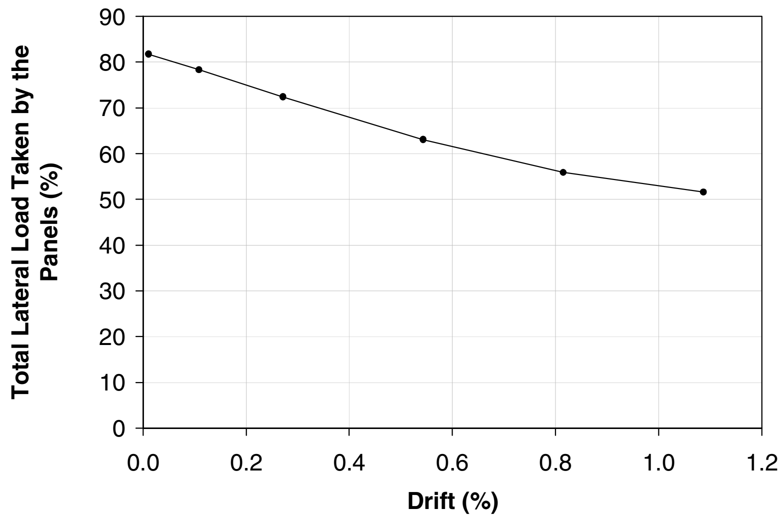


Figure 15: Proportion of lateral load carried by the panels for the beam element frame model.

CONCLUSIONS

A simplified model for full scale structural analysis of a proposed retrofit system was studied. A simple beam model was investigated to simulate the cyclic lateral load response of individual panel experiments. The effect of the retrofit system on a single bay using both a plane stress continuum modeling approach as well as the developed beam model approach was studied.

A mesh dependency was observed for the beam model approach, demonstrating that using 1-2 elements per panel would allow for a more accurate representation of panel behavior. It was shown that including panel slip at the base connection is important for capturing the initial stiffness of the panels. However the proposed modeling approach is not able to capture the peak lateral load capacity of the panel experiments (simulated response was 32% greater than the experimental response) and the amount of hysteretic energy dissipation was also over-estimated. The overestimation of both capacity and hysteretic energy dissipation (i.e. the lack of pinching) is attributed to the reinforcement modeling that did not include bond-slip or a fracture strain.

The beam element frame model presented showed a hysteretic response that was similar to that of a more detailed, plane stress model. Simplifications in the beam element frame produced a slightly lower frame stiffness and more pinching than was present in the plane stress model. Compared with the bare frame, the infill system increases the strength, stiffness and energy dissipation capacity of the frame it is infilling.

Future work will focus on implementing bond slip and steel fracture into the panel models most likely through the use of fiber beam elements. In addition, load rate tests are being conducted to examine the dependency of HPFRCC properties on strain rate. These experiments will indicate whether the finite element models need to incorporate rate dependency. Once these issues have been resolved, full scale structural analyses under seismic loading will be performed using the retrofit system. The optimal placement of the HPFRCC infills throughout the structure will then be examined. The information obtained from full scale analyses (such as interstory drift and floor accelerations) will then be used to address how adequate this retrofit system is in protecting secondary systems in critical facilities.

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