# LARGE SCALE HYBRID SIMULATION TESTS OF EXISTING STEEL FRAME STRUCTURES RETROFITTED WITH INFILL PANELS


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Recent earthquakes around the world have demonstrated that older steel moment-frame structures are seismically deficient since they are susceptible to premature, brittle fracture at their beam-to-column connections. To enhance the seismic performance of these buildings a new seismic retrofit system has been designed and evaluated. The system consists of High Performance Reinforced Cementitious (HPFRC) infill panels acting as energy dissipation fuses that can be easily replaced after an earthquake. The performance evaluation of the infill panel system is validated through two large-scale hybrid simulation tests of a 2-story steel moment-resisting frame, designed in California in 1980s. The experimental program was conducted in the Network for Earthquake Engineering Simulation (NEES) facility at University of California at Berkeley. The test specimen is subjected to a series of design level and maximum considered earthquakes and is proven to be able to reduce maximum story drift ratios and residual deformations of the retrofitted steel moment resisting frame relative to bare frame performance.

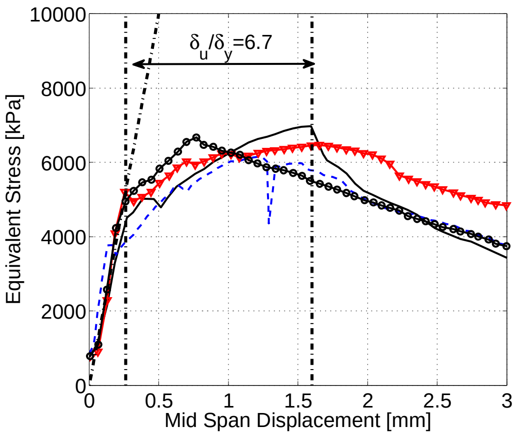

## 1. INTRODUCTION

Recent earthquakes around the world have demonstrated that steel moment frame structures designed based on older seismic provisions «[1]» might be seismically deficient due to premature fracture of beam-to-column connections at fused zone or column flange often noted as “divot” zone «[2]». Important facilities such as hospitals that have been

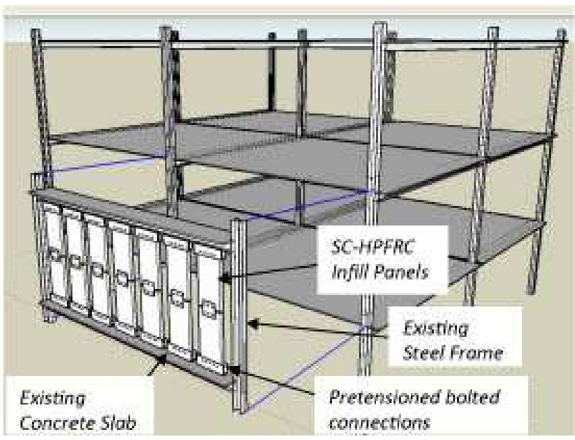
designed in the 1980s and it is likely that their seismic vulnerability is high, should remain operational to minimize human casualties and economic losses after a major earthquake.
Using recent breakthroughs in fiber reinforced concrete technology, Kesner and Billington «[3]» utilized High Performance Fiber-Reinforced cementitious (HPFRC) composites to seismically retrofit vulnerable steel moment frame structures (MRFs). This system was redesigned and evaluated extensively through an experimental program that included a large number of infill panel component tests (see Olsen and Billington «[4]») and a series of large-scale hybrid simulation tests of a 2-story steel moment frame designed in 1980s in California (Lignos et al. «[5]») These tests were conducted at the Network for Earthquake Engineering Simulation (NEES) facility at University of California at Berkeley. This paper discusses the experimental and analytical validation of the proposed retrofit system for existing steel MRFs subjected to earthquakes.

## 2. PROPOSED RETROFIT SYSTEM

A modified version of the self-compacting high performance fiber-reinforced concrete mix that was developed by Liao et al. «[6]» is used in this research. This mix has self-compacting properties and very minimal vibration is used to aid in consolidation. The mix proportion is described in detail in Lignos et al. «[5]». Typical compressive strengths of such a mix range from 6 to 8kPa. High strength hooked steel fibers marked as Dramix RC-80/30-BP are used in the HPFRC mix at 1.2% of the mix by volume. To obtain the tensile properties of the same mix 76mmx76mmx305mm beams are cast and tested using 3-point bending following ASTM standard C 1609/C. *Figure 1a* shows the equivalent bending stress versus strain of one of the ASTM beams. From this figure it can be seen that such mixes can carry tension with a ductility ranging from 3 to 7. This material is utilized to construct an infill panel system that is shown in *Fig. 1b*. The infill panels are precast, and they are intended to be both easily installed and rapidly replaced after an earthquake, if damaged. Each set of two vertical HPFRC infill panels are first grouted into each of two steel channel connections. These connections are pre-tensioned to about 150kN in order to avoid any bolt slip. For this purpose a load-indicating washer is used. The top steel channel connection is field welded at the bottom flange of the upper floor steel beam.



(a) mechanical properties



(b) proposed retrofit system

*Fig. 1 Tension mechanical properties of High Performance Fiber Reinforced Concrete (HPFRC) material of the proposed retrofit system*

The bottom channel connection is bolted to threaded studs that are welded to the top flange of the steel beam of the bottom story. The procedure to be used to weld these studs on the top flange of the bottom steel beam is a proven construction technique referred to by Nelson Stud Welding Inc. The two HPFRC panels are connected at mid-height of a story with a slotted connection. This connection is utilized in order to prevent any build up of axial load in the HPFRC panels and subsequently any out-of-plane movement of the double panel system.

## 3. PROTOTYPE STRUCTURE AND EXPERIMENTAL PROGRAM

### *3.1 Prototype office building*

In order to evaluate the effectiveness of the proposed HPFRC infill panel system discussed in Section 2 of this paper, a prototype steel structure designed in 1980s is utilized. This structure is a 2-story by 3–bay office building with 27x27m rectangular plan view. Its structural system consists of perimeter steel MRFs. The geometric properties of the steel sections of the perimeter moment resisting frames are shown in *Fig.2*. The predominant period of the building is 0.75sec in the loading direction of interest (east-west). The building does not meet the retrofit objectives specified in ASCE 41 «[7]». Thus, it is retrofitted with the HPFRC infill panel system discussed in Section 2. Five individual HPFRC infill panel systems are installed in the first bay of the steel moment frame shown in *Fig. 2*. The period of the retrofitted prototype frame is 0.39sec. A 2/3-scale model of this steel moment resisting frame is scaled based on based on similitude laws «[8]» for strength and stiffness. The steel sections were selected such that the web and flange slenderness ratios $h_f/t_f$, $b_f/2t_f$ are almost the same with the original sections of the prototype moment resisting frame in order to achieve the same component deterioration parameters and minimize scale effects. In summary, the steel MRF consists of W10x45 steel columns, a W14x26 and W10x30 steel beam at the first and second floor, respectively. All the sections are fabricated from A992 Gr. 50 steel. Material properties for these components are summarized in Lignos et al. «[5]».

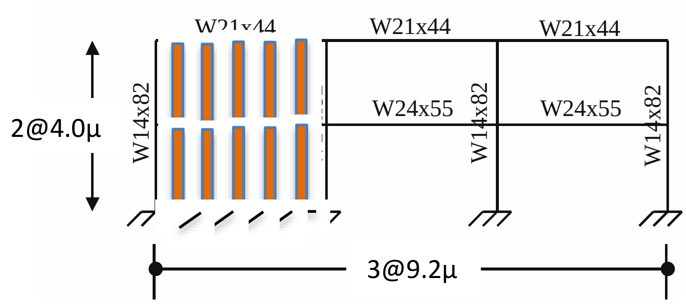



*Fig. 2 Retrofitted steel moment frame designed based on 1980s seismic provisions*

### *3.2 Hybrid Simulation and Test Setup*

The state-of-the art hybrid simulation technique is utilized for the test series discussed in this section. This technique allows testing of the retrofitted part of the moment resisting frame (1-bay frame) only and the rest of the steel moment frame is modeled numerically in the OpenSees «[9]» analysis platform. Deterioration and fracture of beam-to-column connections of the numerical portion of the hybrid model is simulated based on the modified Ibarra-Krawinkler deterioration model implemented in OpenSees «[10]». The Open-source Framework for Experimental Setup and Control (OpenFresco) is used to conduct the hybrid simulations (see Schellenberg «[11]»).

The test frame is built on a self-reacting platform shown in *Fig.3* that was designed for the maximum expected base shear of the test frame during the two testing phases. In order to eliminate out of plane deformations of the test frame, a lateral support system is designed that consists of longitudinal beams that allow sliding of the test frame through slotted sliders that are greased to eliminate friction (see *Fig. 3*). Two 250kips dynamic actuators are connected with the test frame at each floor level. In total, 170 channels were used to instrument the test specimen. A laser scanner was also utilized that scanned the bottom story right column and exterior infill panel. A detailed description of the test setup is discussed in «[5]».

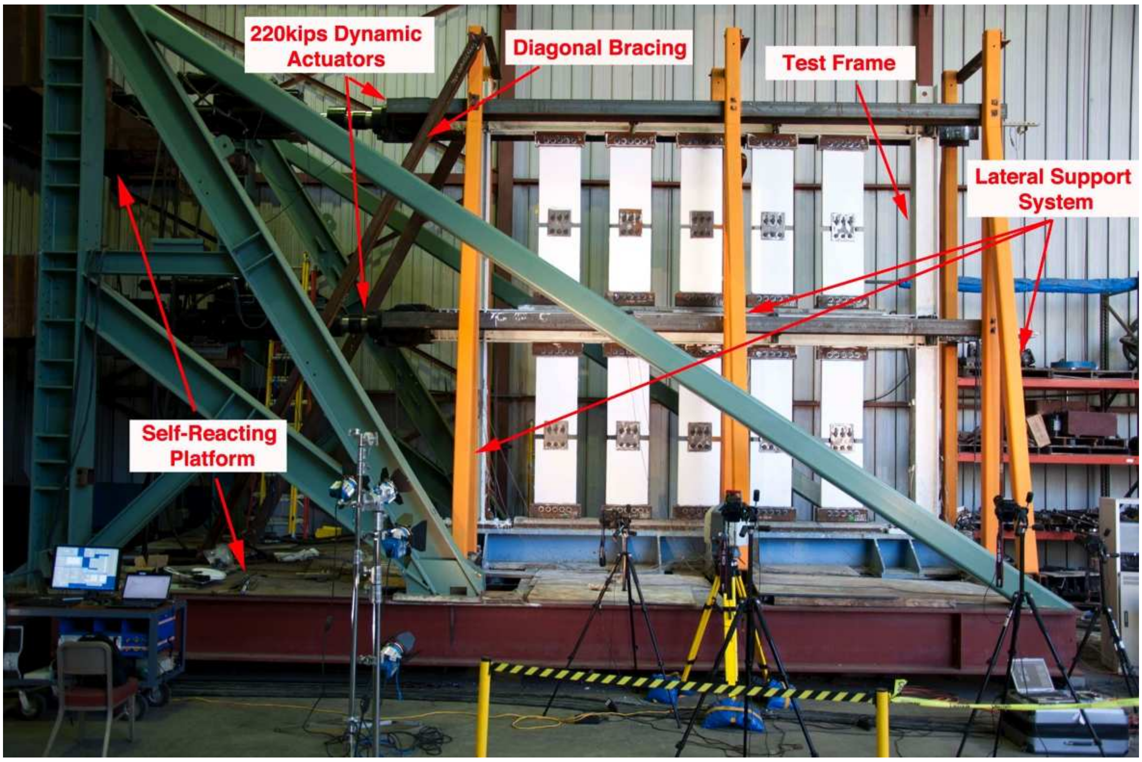


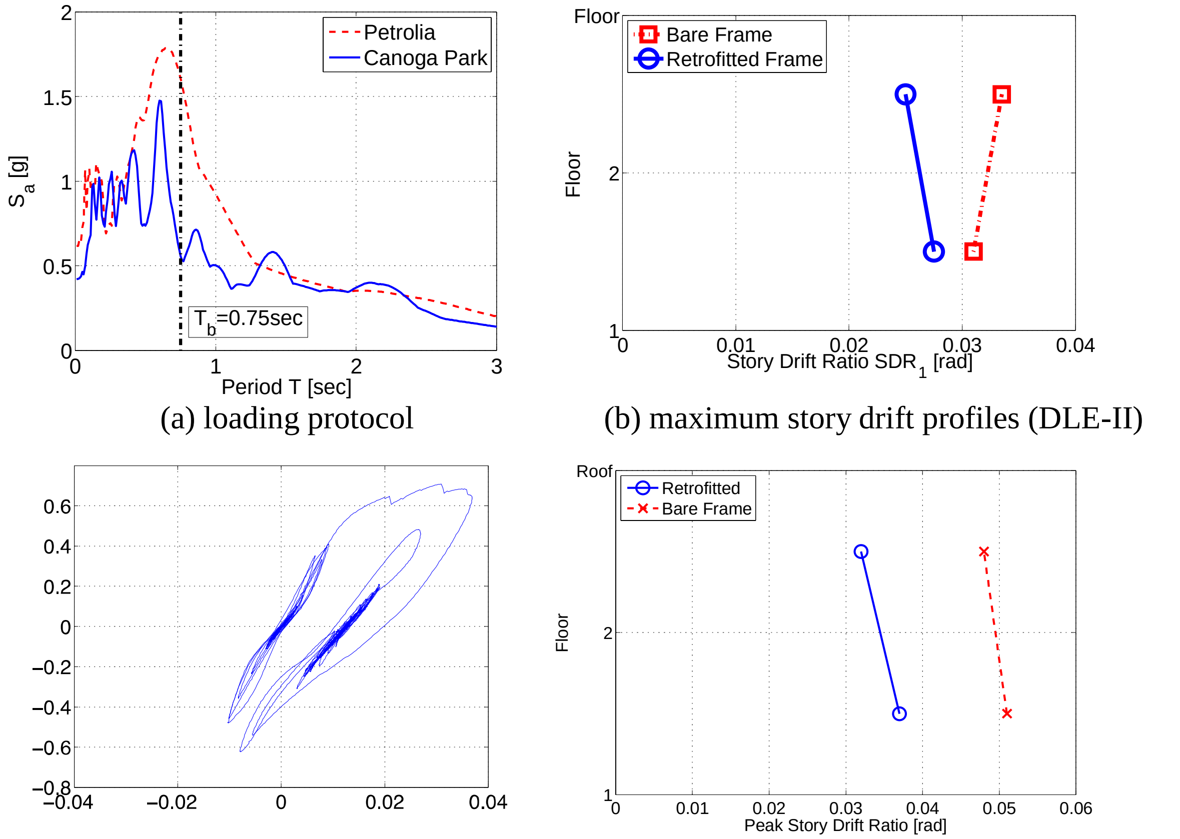

*Fig. 3 Steel moment frame designed based on 1980s seismic provisions*

### *3.3. Testing Protocol and Experimental Results*

Two testing phases are designed for verification of the effectiveness of the proposed seismic retrofit system discussed in Section 3.2. During the first phase, the test frame was subjected to 3 ground motions sequentially. The first ground motion was 30% of the fault normal Petrolia record (1992, Cape Mendocino). This motion represents a Service Level Earthquake (SLE) with 50% probability of exccedence in 50 years at the first mode period of the retrofitted steel MRF. The test frame was then subjected to two Design Level Earthquakes (DLE). The first one was the 70% of the unscaled Petrolia record (noted as DLE-I) and the second one is the unscaled Canoga Park record from the 1994 Northridge earthquake. After completion of testing phase I, all the HPFRC panels were replaced with a new set with nominally identical material properties with the first set of panels. Testing phase II included the same SLE motion with Phase I for comparison purposes, followed by a Maximum Considered Earthquake (MCE), which was the 100% of the Petrolia record. *Figure 4a* shows the unscaled acceleration spectra of the two ground motions used as part of the testing protocol for both testing phases.

During testing phase I, the retrofitted test specimen reached about 1% maximum story drift ratios (SDR) at both stories for the SLE. During the DLE-I (70% Petrolia) the hybrid

model did not exceed more than 1.9% maximum SDR. After the completion of this ground motion the residual SDRs in both stories was less than 0.5%. Similarly, when the hybrid model was subjected to the unscaled Canoga Park record (DLE-II) the maximum SDRs that the specimen experienced were in the order of 3% in the first story. This can be seen from *Fig. 4b* that shows the peak SDRs along the height of the steel moment frame. In the same figure we have superimposed the maximum SDRs of the bare frame response. It is concluded that the infill panel system meets the seismic retrofit objectives.
During testing Phase II, an MCE ground motion followed the SLE. Due to large inelastic cycles prior to the main pulse of the Petrolia record (MCE) distributed flexural cracks were developed in the HPFRC infill panels. Looking at the normalized base shear *V* versus first story drift ratio ($SDR_1$) of the test frame unloading stiffness deterioration occured after the test frame exceeded 3.5% SDR (see *Fig. 4c*). Note that maximum SDRs were reduced by more than 40% compared to the bare frame, as shown in *Fig. 4d*.

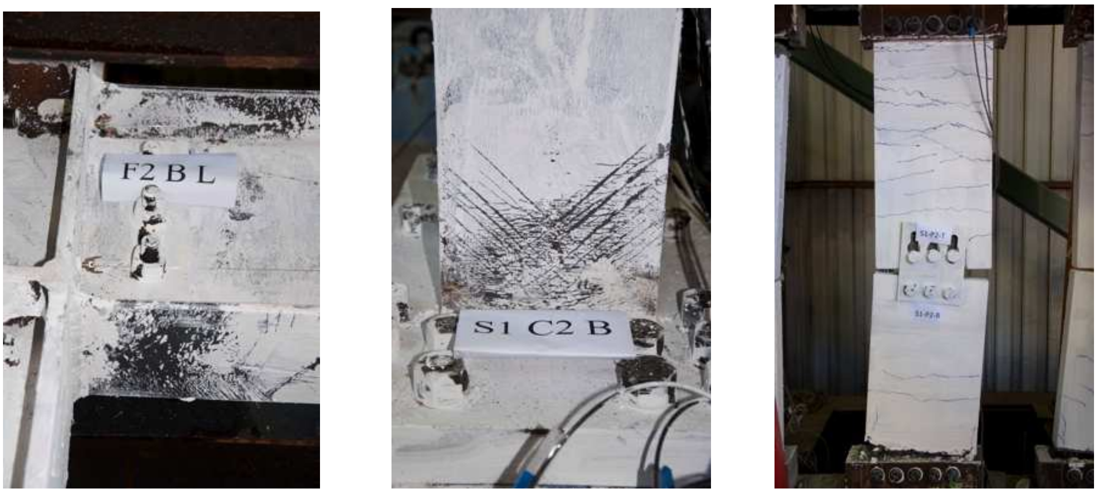



(a) loading protocol (b) maximum story drift profiles (DLE-II)

(c) base shear – $SDR_1$ (MCE) (d) maximum story drift profiles (MCE)

*Fig. 4 Testing protocol and seismic performance of retrofitted steel MRF*

During both testing phases discussed earlier, the structural damage that was observed to the retrofitted steel MRF was primarily yielding at both the first, second floor steel beams and column bases of the steel MRF. This can be seen in *Fig. 5a* and *5b*, respectively. The lack of local buckling, i.e. cyclic strength deterioration, is confirmed from *Fig. 4c*. The unloading stiffness deterioration that is shown in this figure is attributed to the stiffness loss from the failure of HRFRC panels. The primary energy dissipation mechanism that acted beneficially to the overall seismic behavior of the steel MRF was multi-cracking of the HPFRC panels. An example of this mechanism is illustrated in *Fig. 5c*. However, cracking of the HPFRC panels was not as evident as it was in the HPFRC component tests that were conducted before the hybrid simulation tests «[4]». The main reason is the effect of loading history on the seismic performance of these panels and more specifically, a small number of inelastic cycles during an earthquake compared to a large number of inelastic cycles of a standard symmetric loading protocol. A detailed description of the experimental results from the two large scale hybrid simulation tests integrated with analytical simulations that matched relatively well the measured response of the test specimen are summarized in «[5]».




(a) first floor beam (b) column base (c) HPFRC panel

*Fig. 5 Observed damage on the steel structure and the HPFRC panels*

## 5. CONCLUSIONS

This paper summarizes the design and experimental validation of a recently developed infill panel system made of High Performance Fiber Reinforced Cementitious (HPFRC) material for seismic retrofit applications of existing steel moment frame structures. The effectiveness of the HPFRC infill panel system as a seismic retrofit was validated through a two-phase large-scale hybrid simulation testing series that was conducted at the NEES facility of University of California at Berkeley. A 2/3 scale of a 2-story steel moment frame was subjected to a sequence of Design level and Maximum Considered earthquake events. The main conclusions from the testing program are summarized as follows:

1. Inelastic response in terms of peak story drift ratios and residual deformations of the retrofitted moment frame are reduced compared the bare frame performance for both DLE and MCE events.
2. The HPFRC infill panel system was proven to work effectively for a sequence of design level earthquakes without having to be replaced in between design level ground motions.
3. No indication of severe structural damage was observed for both DLE and MCE in any of the structural components (beams and columns) of the test frame, including the numerical portion of the hybrid model.

## 6. ACKNOWLEDGMENT

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# ΜΕΓΑΛΗΣ ΚΛΙΜΑΚΑΣ ΠΕΙΡΑΜΑΤΑ ΣΕ ΥΠΑΡΧΟΥΣΕΣ ΜΕΤΑΛΛΙΚΕΣ ΚΑΤΑΣΚΕΥΕΣ ΕΝΙΣΧΥΜΕΝΕΣ ΜΕ ΠΑΝΕΛΑ ΙΝΟΠΛΙΣΜΕΝΟΥ ΣΚΥΡΟΔΕΜΑΤΟΣ ΜΕ ΧΡΗΣΗ ΤΗΣ ΥΒΡΙΔΙΚΗΣ ΜΕΘΟΔΟΥ

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Σεισμοί που έχουν συμβεί στο πρόσφατο παρελθόν απέδειξαν ότι οι μεταλλικές κατασκευές, οι οποίες έχουν σχεδιαστεί με παλαιότερους αντισεισμικούς κανονισμούς, δεν εμφανίζουν αποδεκτή σεισμική συμπεριφορά αφού οι συνδέσεις τους υπόκεινται σε πρόωρη ψαθυρή θραύση. Για την ενίσχυση της σεισμικής απόκρισης των κτιρίων αυτών σχεδιάστηκε και αξιολογήθηκε ένα νέο σύστημα αποκατάστασης μεταλλικών πλαισίων. Το σύστημα αποτελείται από πανέλα ινοπλισμένου σκυροδέματος υψηλής απόδοσης, τα οποία δρουν ως συστήματα απορρόφησης ενέργειας και τα οποία μπορούν να αντικατασταθούν πολύ εύκολα μετά από έναν σεισμό. Η συμπεριφορά του συστήματος με πανέλα ινοπλισμένου σκυροδέματος αξιολογήθηκε με δύο πειράματα μεγάλης κλίμακας ενός διώροφου μεταλλικού πλαισίου, το οποίο σχεδιάστηκε στη Καλιφόρνια τη δεκαετία του 1980. Τα πειράματα πραγματοποιήθηκαν στο εργαστήριο George E. Brown Αντισεισμικών Ερευνών (NEES) του Πανεπιστημίου της Καλιφόρνιας, Berkeley. Το ενισχυμένο πλαίσιο υπόκειται σε μια σειρά σεισμών σχεδιασμού και σεισμών μεγάλης έντασης και επέδειξε σημαντική μείωση μέγιστης κλίσης ορόφου και παραμενουσών μετατοπίσεων σε σχέση με το μεταλλικό πλαίσιο χωρίς ενισχύσεις.