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Application of Hybrid Composite Material for Improving Dynamic Response of Structures during Sequential Earthquakes – Manufacturing, Testing and Numerical Simulations

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Abstract: Earthquakes continue to expose deficiencies in today's infrastructure and call for engineers to continue to explore new ways to create resilient structures. A disaster, whose implication could result in significant life loss and damages up to the tunes of billions of dollars. An active disaster management scheme for any seismic hazards can involve use of smart composite materials instead of traditional steel reinforcement to dissipate energy and earthquake motion. The use of superelastic shape memory alloy (SMA) fibers with their nonlinear-elastic behavior as reinforcement in the hybrid composite material could potentially provide replacement to steel reinforcement which is prone to yielding and corrosion. Small diameter SMA wires and glass fibers are coupled with polymer matrix to manufacture hybrid SMA-GFRP composite which are sought in this research as reinforcing bars to enhance the dynamic response and seismic performance of typical reinforced concrete (RC) moment resisting frame (MRF). Manufactured coupon specimens are tested to achieve constitutive behavior which is used to calibrate numerical material models. These verified material models are subsequently extended to structural models of MRF reinforced with hybrid SMA-GFRP composite and steel to perform the inelastic sequential seismic analyses. Results from use of SMA-GFRP composite bars show disaster mitigation through reduction in residual inter-storey drifts of reinforced concrete frame while maintaining elastic characteristics.

1 INTRODUCTION

Majority of structural failures that occur during earthquakes are due to the collapse of one or more of the reinforced concrete (RC) members. Post eathquake research studies have shown that the main factors causing the failures of RC members are their insufficient flexural ductility [1]. Yielding and rupture of reinforcement in the plastic hinge region of the columns and beams has been identified as the main reasons for the poor flexural ductility observed in many of the collapsed structures [2]. Steel which has been used as reinforcement since last century in almost all reinforced concrete structures is prone to yielding which causes permanent damage to the structure. The most critical drawback in currently used steel reinforcement in RC structures is susceptibility to accumulation of plastic deformation under seismic loading. Steel reinforced structure dissipates energy through the hysteretic action of material and structure during an earthquake event. This hysteretic action results in permanent damage to the steel reinforcement and the structure. Yielding of steel and development of cracks in concrete will cause permanent interstorey drifts in the structure, which is residual even after the seismic event has finished.

To address the issue of yielding, ductility without permanent deformation and material degradation such as corrosion, this study investigated the use of a new type of hybrid composite, known as shape memory alloy-GFRP (SMA-GFRP) as reinforcement for RC structures. Hybrid composite materials are the most adaptive engineering material and are referred to as a combination of two or more distinct materials into one engineering material. History has shown that the more capable the material is, the greater the scope for ground breaking engineering achievement. As shown in a schematic in Fig. 1(a), a SMA-GFRP reinforcing bar comprises polymeric resin reinforced with small diameter superelastic SMA fibers. The typical flag shape hysteresis of superelastic SMAs shown in Fig. 1(b) is a direct result of a reversible stress-induced phase transformation between austenite and martensite phases. The nonlinear, yet pseudo-elastic behavior typical of SMA fibers [3] will allow SMA-GFRP composite reinforcement to exhibit hysteretic and ductile behavior with minimal damage to the RC structure.

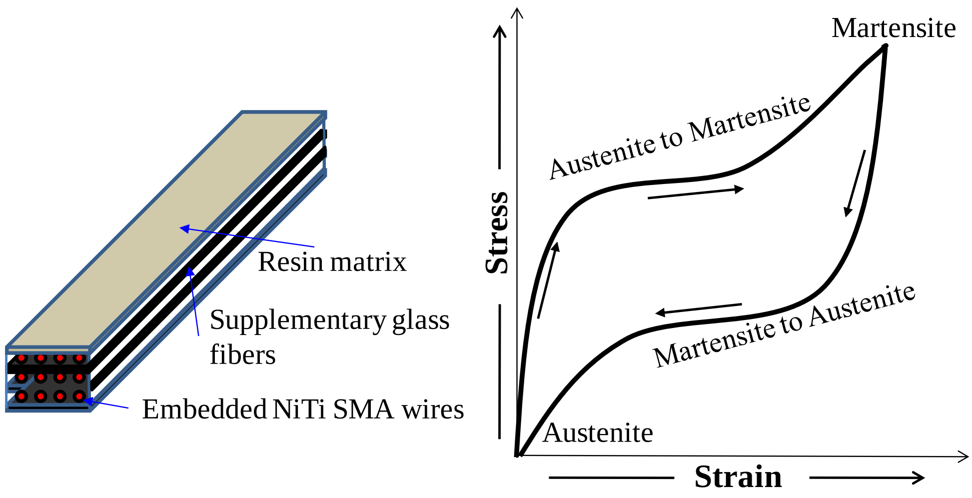

Figure 1: Schematic drawing (a) 100% SMA composite rebar cross-section. (b) Stress-strain hysteresis of superelastic SMA.

Initially, the aim is to fabricate SMA-GFRP composite and evaluate its mechnical material properties, followed by development of analtical models capturing their constitutive behavior. This will lead to acheive the primary focus of the study which is to explore the use of SMA-GFRP bars as reinforcement in RC moment resisting frame (MRF) structures subjected to earthquakes as an active disaster mitigation technique. For the reason that there is high stress concentration in plastic hinge zones of beams and columns in MRF, the proposed SMA-GFRP composite is placed in beam-column joints while rest of the frame is reinforced with GFRP. The performance of designed MRFs subjected to seismic forces, is then analytically compared between use of steel and SMA-GFRP reinforcement types. The results of this study showed that SMA-GFRP reinforcement has the capability to dissipate energy while exhibiting high ductility, with negligible residual inter-storey drifts.

2 MANUFACTURING AND TESTING OF SMA COMPOSITE MATERIAL

As a first step, ingredients for manufacturniug of hybrid composite were selected which included SMA wires, embedded in epoxy matrix, supplemented with conventional fibers. In a previous study by authors [4], NiTi (NiTi-51%-49%) SMA wires with a diameter of 500μm were selected and trained through continued cycling to stabilize mechanical properties for manufacturing of SMA-GFRP composites. Glycidyl ether epoxy (Epoxy-862) and Polyamine curing agent (Epikure-3274) in 100:40 pbw ratios were selected as constituents of host resin matrix. Out of various commercially available fiber types (such as E-glass, Carbon and Kevlar), S-glass was selected as supplementary reinforcement in the composite because of good elongation properties before fracture (as high as 3.4% strain).

Trained SMA wires were embedded in this resin matrix with and without additional supplementary glass fibers to fabricate SMA-GFRP composite under specified temperature and pressure, using hot-press. Two composite specimens, one reinforced with only SMA wires (Fully reinforced composite, FRC), and second reinforced with SMA wires and additional glass fibers (Partially reinforced composite, PRC) were fabricated. Manufacturing process for SMA-GFRP hybrid composite is summarized in Fig. 2.

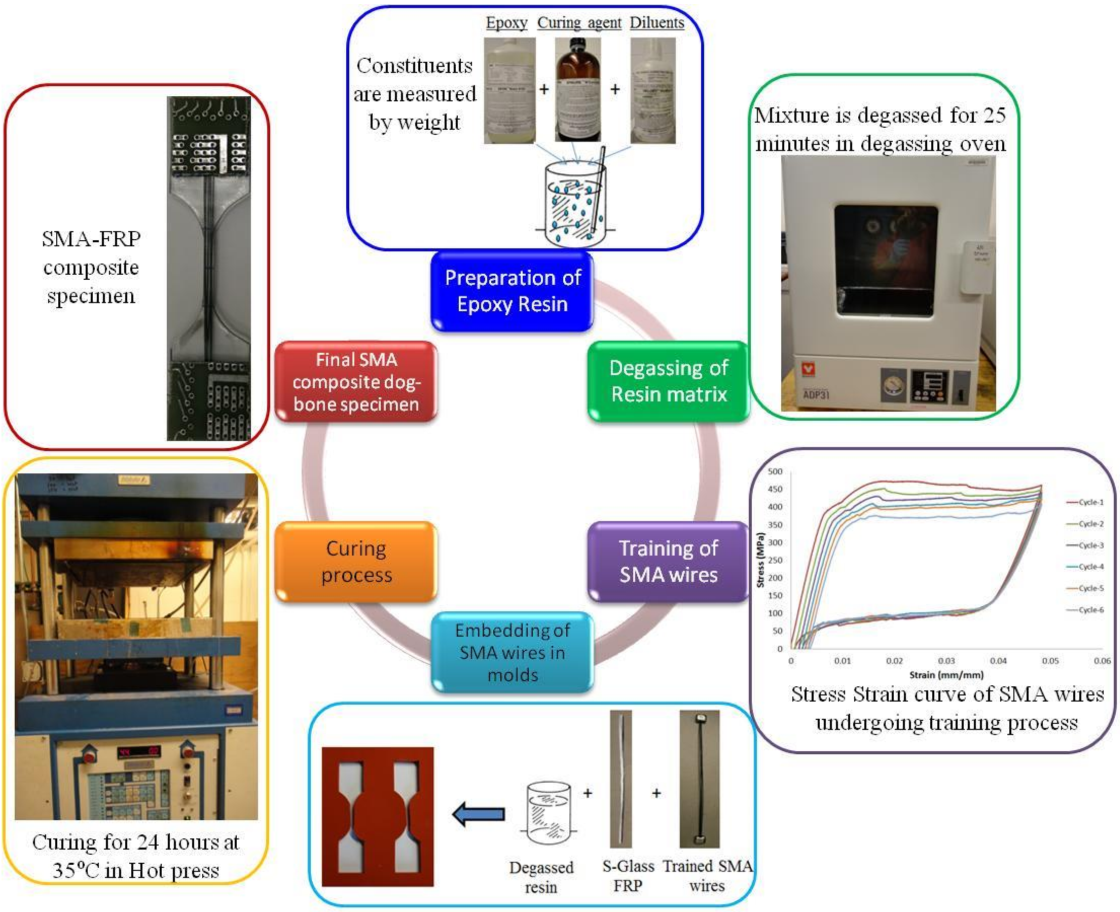

Figure 2: Summary of Manufacturing Process for SMA-FRP Hybrid Composite.

Both composite specimens were designed to achieve target initial composite modulus (E_c) of 13.74 Gpa, which required FRC and PRC specimens to be reinforced with 7 and 3 SMA wires, respectively. The reinforcement volumetric fraction including SMA wires and additional glass fibers for FRC and PRC specimens was 20.3% and 17.7%, respectively. Table 1 shows specifications of both SMA-GFRP composite specimens. Both the composite specimens were tested under quasi-static cyclic tensile loading to achieve constitutive material response. Fig. 3 shows the illustration of loading frame test setup.

Table 1: Fiber volume fraction of SMA-FRP composite specimens

Specimen	SMA-FRP Composite				
	Number of SMA Wires	**SMA Fraction (%)**	**GFRP Fraction (%)**	**Total Fiber Volume Fraction (%)**	**Modulus (E_c) GPa**
FRC	7	20.3	-	20.3	13.7
PRC	3	8.4	9.3	17.7	13.7

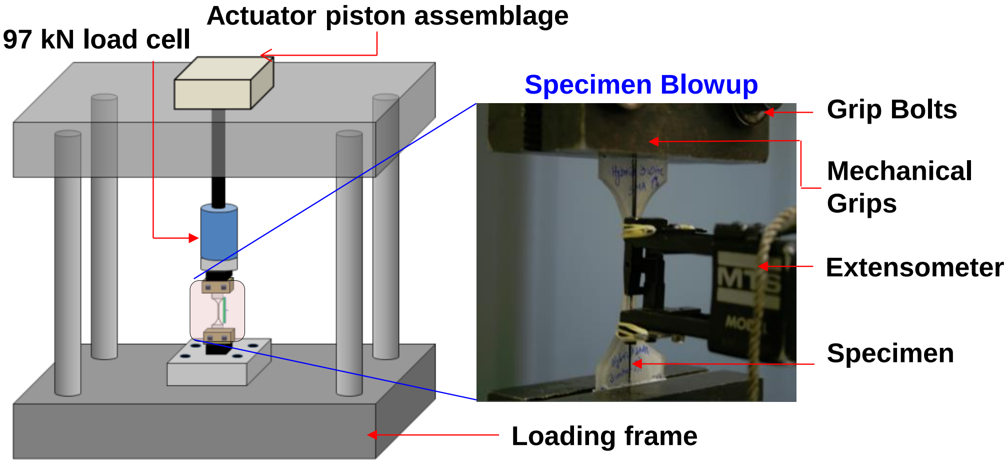

Figure 3: Schematics of close up of SMA-GFRP composite specimen loaded in mechanical grips

Fig. 4 shows the uni-axial tensile testing results of the two SMA-GFRP composite. Results show that adding SMA fibers to the composite matrix significantly enhanced the hysteretic energy dissipation capability of the composite while exhibiting decreased accumulated residual strains. The re-centering capabilty exhibited by SMA-GFRP composite without inhereting damage is a hallmark property for reinforcement to sustain dynamic loading and seismic mitigation.

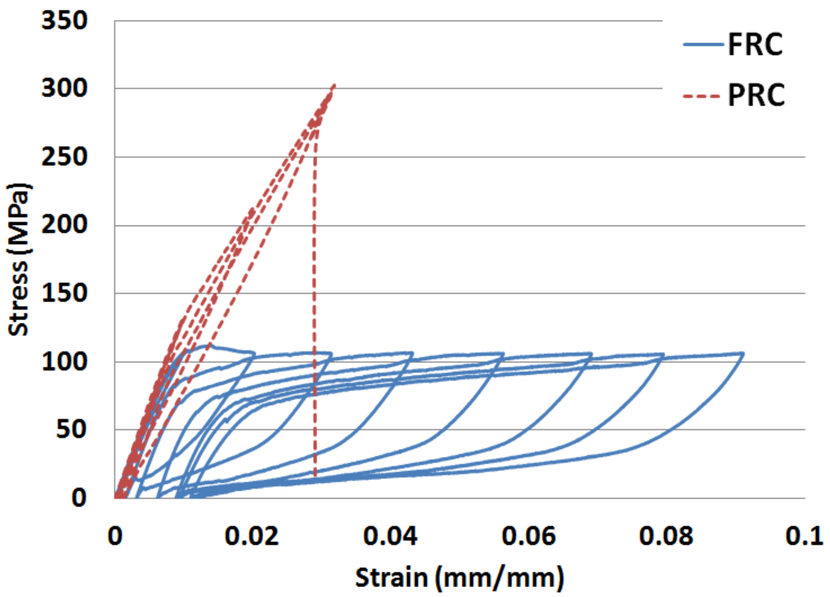

Figure 4: Comparison of stress strain curves of FRC and PRC specimens

3 NUMERICAL MODELING AND VALIDATION

The experimental results from the quasi-static testing were utilized to develop numerical material models for both FRC and PRC composites. Table 2 shows detailed properties of each material obtained from experimental tests and utilized in developing the model. Fig. 5 shows schematic of stress-strain curves for each material utilized to develop numerical models for SMA-GFRP composite. To develop stress-strain models of the composite, fiber section approach was used. SMA uniaxial material model available in OpenSees [5] library was used to represent the behavior of SMA wire, elastic perfectly plastic (EPP) uniaxial material model was used to model the resin, while linear elastic material was used for depicting the behavior of glass fibers. Parallel material command was employed to link the epoxy and SMA/glass fiber material models, in which the strains are equal while stresses and stiffness's are additive.

Table 2: Material properties used in numerical models obtained from experimental tests

Material	Property	Abvn.	Value
Resin	Young's Modulus	E_m	1.57 GPa
	Yield Stress	Fy	32 MPa
SMA	Young's Modulus	E_{SMA}	65 GPa
	Austenite to Martensite start stress	σ_{AMs}	500 MPa
	Austenite to Martensite finish stress	σ_{AMf}	510 MPa
	Martensite to Austenite start stress	σ_{MAs}	135 Mpa
	Martensite to Austenite finish stress	σ_{MAf}	145 Mpa
Glass fibers	Young's Modulus	E_f	86.7 GPa
	Rupture strain	ε_f	3.4%

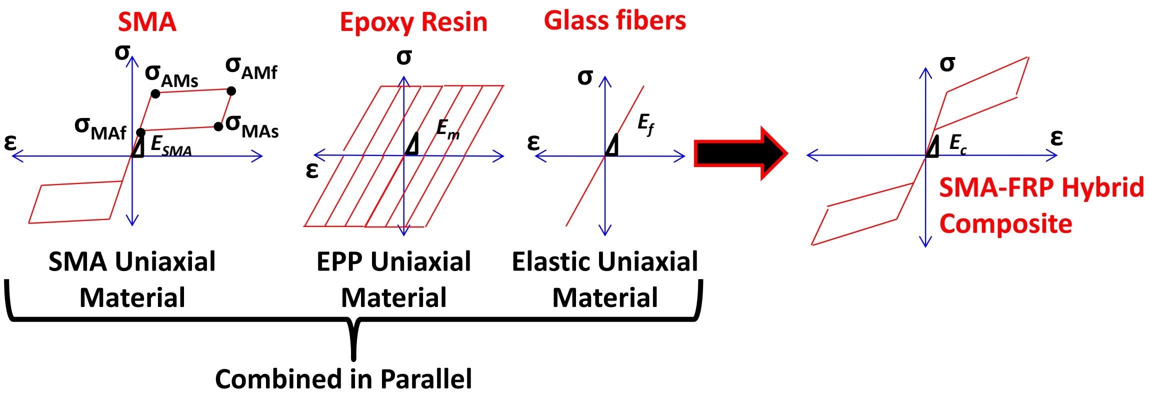

Figure 5: Schematic of back bone stress-strain curves for various materials utilized to develop numerical models for SMA-FRP hybrid composite

Fig. 6 shows comparison of experimental results and numerical model results for FRC and PRC composite specimens. Results show that the numerical models are able to depict the initial modulus and strength characteristics in addition to hysteretic behavior and accumulated residual strains of the composite for different strain levels and volumetric ratios. Numerical models are also able to capture the forward and reverse transformation associated with change of phase in SMA material. Once the developed models were able to capture the experimental constitutive behavior of composites, the input parameters could be calibrated and modified for other proportions of each ingredient of the composites. After the SMA-GFRP composite material models were calibrated, they were incorporated in SMA-GFRP composite reinforced structural frame models.

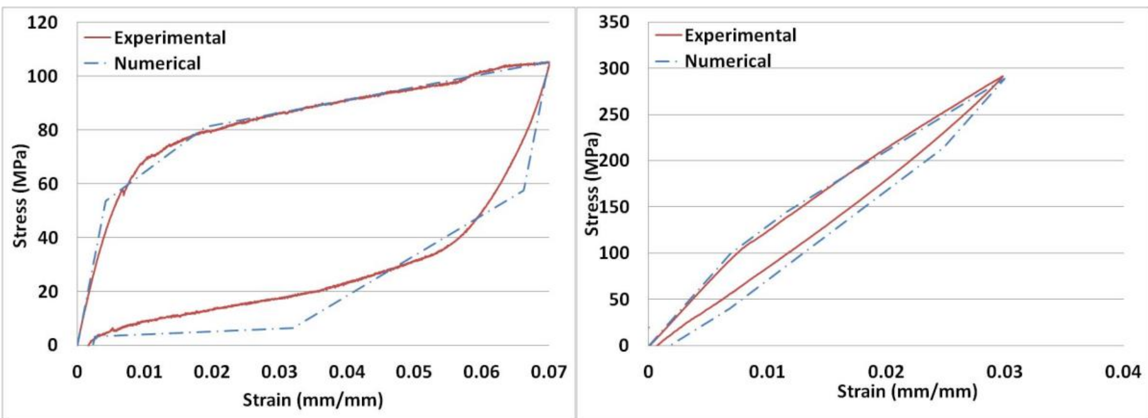

Figure 6: Comparison of experimental results and numerical models (a) FRC (b) PRC composite

4 SCANNING ELECTRON MICROSCOPY IMAGES

For this study, SEM images were utilized to investigate the damages and anomalies like de-bonding / de-lamination between resin and SMA, fracture of FRP fibers, efficacy of resin in filling all air voids and overall layout of composite specimen. These images acted as tools to confer the manufacturing technique which was established after many trials. For this purpose, all composite specimens used for SEM imaging were acquired from tested / damaged specimens and underwent surface polishing. Fig. 7a shows a back-scatter electron (BSE) image of PRC composite specimen with 200X magnification and a blow up with 1200X and 5000X magnification in Fig. 7c and Fig. 7b, respectively. BSE images allow achieving contrasting images of the cross section which helps in identifying material with different densities. Fig. 7d shows secondary electron (SE) image at 5000X magnification to see the depth and contours of the cross section. Image shows complete enveloping of resin around tiny glass fibers and SMA wire, proving good penetration capability and cavity filling of the selected resin matrix system. BSE image with show absence of voids and de-lamination between SMA, glass fiber and resin matrix, depicting good bond.

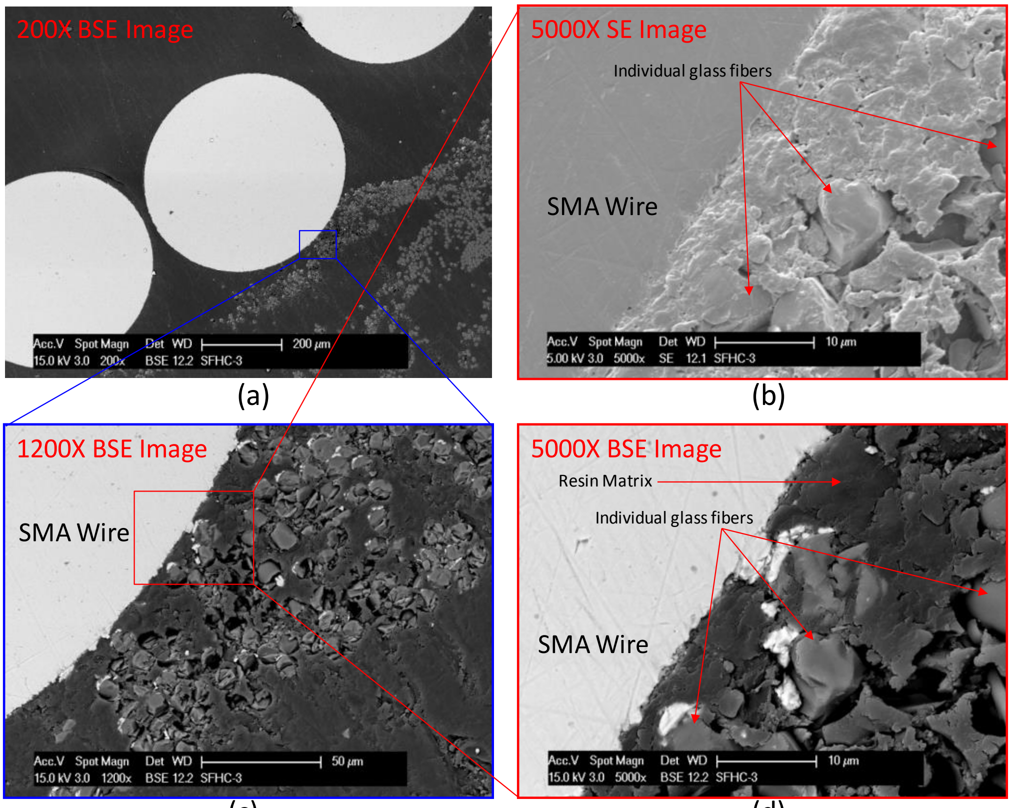

Figure 7: SEM images of PRC composite. (a) BSE image with 200X. (b) SE image with 5000X. (c) BSE image with 1200X. (d) BSE image with 5000X.

5 STRUCTURAL NUMERICAL MODELING OF RC MOMENT RESISTING FRAMES

Finite element program, OpenSees which has been specifically designed for seismic analysis and earthquake simulations, was utilized to develop the composite constitutive models. A 2-D three-storey, single-bay RC MRF was modeled to investigate the behavior of steel and SMA-GFRP composite reinforcement. Fig. 8 shows details of frame configuration, layout of the reinforcement at the plastic hinge region, and cross sections of beam and columns utilized to develop the analytical model. The frame has a bay width of 6.5 m and story height of 3.6 m for all three stories. Nonlinear beam-column elements with fiber sections were used to model the moment resisting frame elements with distributed plasticity. In order to restrict the cost of material associated with use of NiTi SMA in the SMA-GFRP composite, the reinforcing composite was only provided in the plastic hinge zones of MRF where high inelasticity is expected to develop. Rest of the frame was reinforced with conventional glass-FRP (GFRP) rebars. For frame analysis, it was assumed that SMA-GFRP composite reinforcement constitutes of 65% fiber and 35% resin in terms of volumetric ratio. Predefined models of Steel02 and Concrete02 in OpenSees were used for representing grade 60 steel with 200 GPa and concrete with unconfined compressive strength of 30 MPa. Perfect bond was also assumed between all reinforcement types and concrete material. More details related to the structural modeling technique adopted in this study can be found in [6].

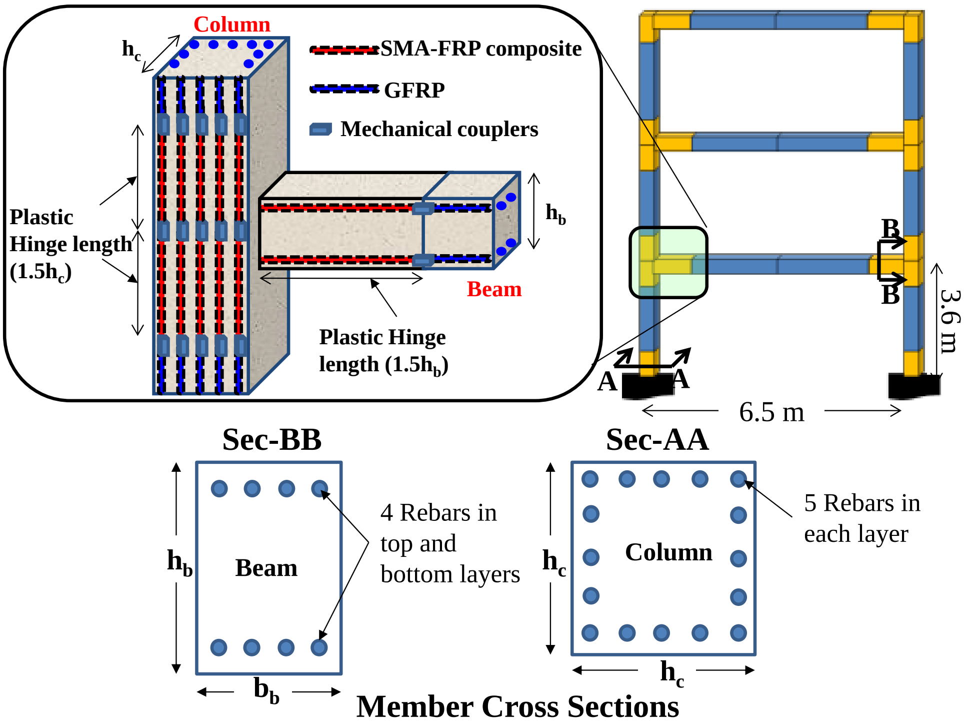

Figure 8: Schematics of MRF configuration utilized in numerical modeling

6 PERFORMANCE BASED DESIGN OF MRF

Performance based design approach was used for designing the MRF with steel and SMA-GFRP. Performance based engineering (PBE) involves use of peak lateral displacement demands and capacities as mean to assess the structures performance during a seismic event. Generally, performance objectives are pre-quantified by the inter-story drift ratio (IDR) limit, which has become a common earthquake demand parameter (EDP) that is used for assessing the damage in structures [7]. Since interstory drift ratio (IDR) values larger than 3% may result in irreparable structural damage or collapse [8], the maximum IDR limit state adopted in this study, was 3%. Displacement based design approach was adopted by incorporating capacity spectrum method (CSM) as defined by Applied Technology Council (ATC-40) [9]. The procedure compares the capacity of the structure (in the form of pushover curve up to target IDR) with the demands on the structure (in the form of response spectrum). Many researchers have suggested modification to the ATC-40 procedure for adaptation as design tool [10]. This iterative process allows design of structure for certain seismic demand. Capacity spectrum in comparison with response spectrum for various effective damping ratio for SMA-GFRP composite reinforced MRF at 3% target IDR is shown in fig. 9. The selected beam and column dimensions for MRF designed for 3% IDR demand were 300x500 mm and 450x450 mm, respectively for all three frames. The final reinforcement ratios for beam and columns in all three frames reinforced with steel, SMA-GFRP and GFRP are shown in table 3.

Table 3. Reinforcement ratio for the designed column and beam cross-sections

Performance Limit State	Reinforcement Ratio (ρ-%)				Fundamental Period (Sec.)		Ultimate Strain Core Concrete
	Beam		Column				
	Steel	SMA-GFRP	Steel	SMA-GFRP	Steel	SMA-GFRP	
3% IDR MRF	1	1.5	2.56	3.8	0.46	0.52	1.4%

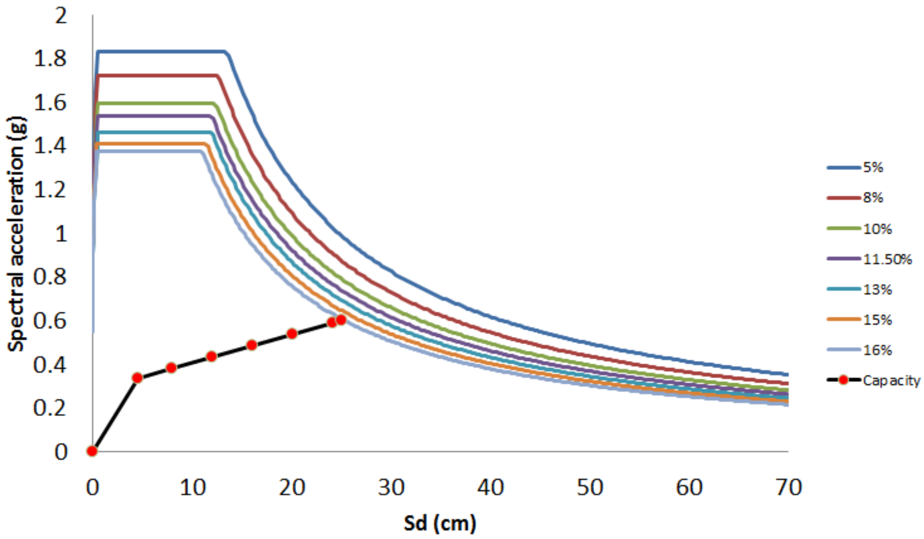

Figure 9: Capacity spectrum vs. response spectrum for various effective damping ratio for SMA-GFRP composite reinforced MRF at 3% target IDR

7 SEQUENTIAL SEISMIC ANALYSIS

Structural seismic performance is often based on response of structures to single major main shock seismic event. However, it is a common fact that aftershocks are often strong enough to cause serious damage and even collapse of structures, especially those which were already damaged during the main shock [11]. Recent earthquakes (Christchurch 2010) have shown effects of aftershocks on reinforced concrete (RC) buildings in terms of damage accumulation and permanent residual drifts due to plasticity of reinforcing steel. For this reason main-shock aftershock sequence from Christchurch 2010 has been used as input earthquake loading (7.1 Mw for main and 6.3 Mw for aftershock). Incremental dynamic analysis (IDA) method was used in this study to evaluate the response of the frames under varying seismic loading [12]. IDA method involves subjecting a structural model to one or more ground motion records. Each record is then scaled to multiple levels of intensity, thus producing one or more load displacement curves. The primary goal of IDA technique is to quantify the reserve capacity of the structure against target performance level under scaled ground motion frequency content.

In step-1 of the analysis, the main shock record was scaled incrementally using scaling factors (S.F.) until the target IDR (3%) is reached in all three designed MRFs with steel and SMA-GFRP reinforcement. In the subsequent analysis in step-2, the scaled main shock (from step-1) and the original aftershocks were combined together to form a single sequential ground motion record and was again applied to each MRF. A time gap was applied between each scaled main shock and aftershock record of 50 seconds to curb any transient vibration. The aftershock part of the sequential record was then scaled to different intensity levels until the scaled sequential ground motion record again causes target IDR in the MRF. Drift time history for both the MRF's with steel and SMA-GFRP reinforcement were developed to determine the corresponding PGA which would satisfy the target performance level. Accumulations of residual IDR in all three frames were also recorded for each earthquake sequence. Fig. 10 shows the IDR time history of all three MRF when subjected to a sample case of Christchurch earthquake sequential records.

Main shock (original 0.149g) from Christchurch earthquake was required to be scaled to a PGA of 0.61g and 0.52g to cause 3% IDR for steel and SMA-GFRP reinforced frames, respectively. The aftershock (original 0.52g) from Christchurch earthquake had to be scaled to a PGA of 0.53g and 0.5g to reach the target performance limit state for steel and SMA-GFRP reinforced MRF-3%, respectively. Steel reinforced MRF-3% accumulated 0.3% and 0.65% residual IDR from main and aftershock sequence, respectively. This net residual IDR increase by 117% is due to sequential earthquake influence. On the other hand, because of re-centering capability of SMA composite reinforcement, there was no accumulation of permanent damage or drift in SMA-GFRP reinforced MRF. Because of yielding and permanent damage, steel MRF experienced residual IDR for both main and aftershocks once scaled to target drifts.

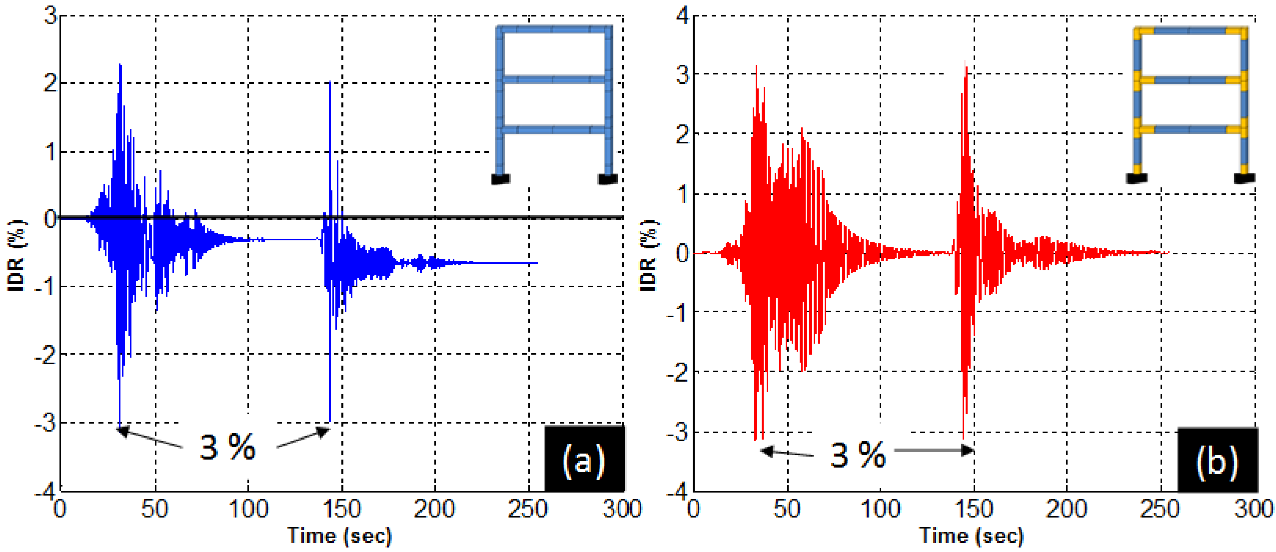

Figure 10: IDR time history response subjected to Christchurch sequence event (a) Steel reinforced MRF (b) SMA-GFRP reinforced MRF

8 CONCLUSION

Study / results showed that the RC structures reinforced with steel are very much vulnerable to impact of earthquake hazard especially under seismic sequence as they already are weakened due to yielding and damage accumulation resulting in permanent residual inter-story drifts (IDR). Lack of any experimental research and absence of guidelines by any governing body to account for multiplicity earthquake effect has made this problem more perplexing. Challenges offered by multiplicity earthquake effects is to develop a more robust reinforcing material which allows re-centering capability, such as proposed in this study by using SMA-GFRP hybrid composite. Results of this research indicated use of SMA-GFRP hybrid composite in plastic hinge zones of RC MRF under single or multiple seismic hazards, as an effective strategy to provide ductility, dissipate energy through hysteresis while providing re-centering capability. These desired properties make SMA-GFRP hybrid composite reinforcement an ideal replacement to steel and GFRP reinforcements in selected plastic hinge lengths / zones of MRF. Results from this study indicate promising effects by adopting suggested fabrication procedure for SMA-GFRP hybrid composite. Use of such smart materials has potential to provide proactive solution to mitigate any seismic hazard by reducing residual IDR and enhancing relative ductility.

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