EVALUATION OF RETROFIT EFFECTIVENESS AND COST IMPLICATIONS OF MRF STRUCTURES USING DISTINCT FRCM COMPOSITE SYSTEMS

ROSHEN JOSEPH1, AMAN MWAFY1, and M. SHAHRIA ALAM2

1Dept of Civil and Environment Engineering, United Arab Emirates University, Al Ain, UAE
2School of Engineering, The University of British Columbia, Kelowna, Canada

This paper summarizes the results of a numerical investigation to assess the effectiveness of retrofitting pre-seismic code concrete framing structural systems using two distinct fiber-reinforced cementitious matrix (FRCM) composites. While FRCM composites were focused in the literature at the member level, this study focuses on implementing this retrofit technique effectively at the structure level. Several static pushover analyses (SPAs) and inelastic dynamic simulations (IDSs) are carried out for FRCM-retrofitted RC frames representing the lateral force-resisting system of a moment-resisting frame (MRF) structure. Correlating the numerical simulation results and experimental results obtained from another study verified the selected fiber discretized section modeling technique for FRCM retrofitted MRFs and reflected the effectiveness of the adopted approach in prolonging local and global damage states. The verified modeling technique of the risk-mitigation measure is then employed to evaluate the performance of an upgraded RC building using three-dimensional fiber-based numerical models. Finally, a parametric study using SPAs and IDSs using multiple seismic scenarios is conducted to select the most effective FRCM retrofit material for the seismic performance enhancement of the benchmark structure. The study concludes that using the selected FRCM retrofit technique effectively mitigated the structural collapse damage state of the substandard building at the design and maximum considered seismic intensity levels by 28% and 32%, respectively.

Keywords: Seismic retrofit, Substandard structures, Numerical simulation, Fiber-based modelling.

1 INTRODUCTION

During strong seismic events, certain components of buildings built before the implementation of seismic codes, especially the structural columns are unable to withstand extensive displacement demands without incurring substantial structural damage. Additionally, in the case of deficient reinforced concrete (RC) structural systems, the formation of plastic hinges in vertical elements at low levels of ductility can pose a significant risk during earthquakes, necessitating the enhancement of their flexural capacity. Effective retrofit techniques can improve the seismic performance of RC columns. While several previous studies focused on conventional retrofit measures to improve the seismic performance of substandard structures, using innovative composite materials is crucial as traditional seismic-risk mitigation alternatives such as FRP wrapping suffers several drawbacks, namely poor capability in raised temperatures, lack of vapor permeability, and incompatibility with concrete surfaces (Mwafy and Elkholy 2017, Joseph et al. 2022). FRCM, known as ‘Fiber-
Reinforced Cementitious Matrix’ has been proposed as an effective retrofit substitution to FRP wrapping to retrofit concrete members. The FRCM composite consists of high tensile strength textile fibers in addition to cementitious mortar. Along with fire-resistant property, the application of this composite material is suitable for concrete surfaces. Considering the merits of this contemporary retrofit technique, many researches for retrofitting structural members deficient in bending and shear capacity and improving the seismic capacity of RC columns using FRCM systems have been reported in the literature (Trapko et al. 2015, Koutas et al. 2019). On the other hand, previous studies also implied that a premature debonding failure mechanism was observed in FRCM-retrofitted concrete elements before attaining the ultimate strength of the composite system, compromising the effectiveness of this technique (Babaeidarabad et al. 2014). This premature failure mode can be delayed using effective anchoring systems (Koutas et al. 2019). However, there is still a dearth of research on the seismic loss-estimation investigation of pre-code RC buildings vulnerable to bending and shear failure using different FRCM materials and effective spike anchor systems. Therefore, in the present study, the impact of implementing two FRCM composites (i.e., PBO and carbon) with a custom-fabricated textile-based anchor system to a benchmark MRF building is assessed numerically, aiming to prioritize an effective seismic risk mitigation systems to improve the seismic capacity of substandard buildings considering the material cost.

2 NUMERICAL MODELLING APPROACH

Previous experimental investigations were carried out to assess the technical properties of the FRCM system (Arboleda et al. 2012). Design guidelines and previous studies have adopted the mechanical properties of the PBO and carbon FRCM composite systems listed in Table 1 (ACI Committee 549 2013, Marcinczak et al. 2019). Reviewing previous studies on FRCM-retrofitted structures reflected the need to evaluate the seismic behavior of verified FRCM retrofit approaches for a substandard building representing a low-rise framing structural system of a concrete building. Therefore, the present study selected a residential two-story MRF structure which is 8.5 m in height having five framing systems spaced at 4.0 m in the short direction as a benchmark structure. The floor layout of the building measures 16 m × 13 m. The columns inside the building were 200 × 400 mm, whereas the columns at the periphery are 200 × 300 mm. The composite retrofit approach installed on RC column is modeled using jacketed fiber-based elements for the retrofitted MRF structure, as shown in Figure 1. These columns were numerically modeled using inelastic displacement-based formulations for the non-linear simulations. RC slabs was considered using fiber discretized sections (Joseph et al. 2022). In the fiber-based modelling approach, jacketed RC sections are used to model the retrofitted sections. The jacketed material applied on the RC columns is the cementitious mixture of the FRCM system. The external reinforcement considered is the combined contribution of the spike anchors and textile fibers in longitudinal orientation with appropriate material properties of the FRCM system. Following the recommendation of the fiber-based analysis platform, anchor spikes and PBO fibers in the longitudinal reinforcing bars of columns are constituted by using a uniaxial trilinear FRP model using the tensile strength, initial stiffness, and post-peak stiffness of the retrofit application, as previously discussed (ACI Committee 549 2013, Marcinczak et al. 2019, SEISMOSOFT 2022). Taking into account the impact of FRCM spike anchors, FRCM plies, and the direction of the fiber sheets, the external reinforcement depicted in the cross-section of the jacketed column in Figure 1(b) possesses an equivalent cross-sectional area that comprises the total PBO fibers in the vertical orientation. Moreover, values of confinement factors used for the retrofit system are computed as per the recommendation of CNR-DT200 (Ruredil 2009, CNR 2013).
Table 1. FRCM composite system properties (ACI Committee 549 2013).

<table>
<thead>
<tr>
<th>Technical Properties of FRCM</th>
<th>PBO</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean uncracked elastic modulus of FRCM composite (GPa)</td>
<td>1805</td>
<td>512</td>
</tr>
<tr>
<td>Mean cracked elastic modulus of FRCM composite (GPa)</td>
<td>128</td>
<td>80</td>
</tr>
<tr>
<td>Mean ultimate tensile strength (MPa)</td>
<td>1664</td>
<td>1031</td>
</tr>
<tr>
<td>Mean ultimate tensile strain, %</td>
<td>1.7565</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Figure 1. Illustration of the adopted numerical modeling approach: (a) FRCM retrofitted structure; and (b) cross-section of the FRCM retrofitted column.

3 LATERAL CAPACITY OF RETROFITTED SUBSTANDARD STRUCTURE

Figure 2(a) depicts the three-dimensional numerical representations of the reference framing systems along with the strengthened alternatives. Figure 2(b) illustrates the pushover results and mapping of the local failure criterions of the two-story structure and selected seismic risk mitigation techniques using FRCM systems. The time period of the low-rise substandard structure along with its PBO and carbon retrofitted options are 0.807 secs, 0.770 secs, and 0.773 secs, respectively. The FRCM retrofit techniques result in a slight improvement in elastic stiffness and a significant increase in lateral strength and ductility capacity of the substandard building, with improvements of 61% and 45% for flexural performance and 42% and 39% for ductility capacity using the PBO and carbon retrofit techniques, respectively. It is also observed that the retrofit measures prolong the occurrence of local failure modes, mainly concrete crushing and rebar buckling occurring in columns.

Figure 2. Comparison between the pushover curves and mapping of local failure criteria of the substandard and retrofitted buildings: (a) existing and composite system retrofitted buildings; and (b) mapping the onset of local failure criteria on the pushover results of the existing and retrofitted framing systems.
4 PROBABILISTIC SEISMIC PERFORMANCE ASSESSMENT

For more detailed seismic performance assessment, several inelastic multi-record incremental dynamic simulations (IDSSs) are undertaken on the benchmark and strengthened structures till the fulfilment of different performance criteria. Eleven far-field (FF) input ground motions are selected to capture the structures’ seismic performance in IDSSs as they represent the most significant seismic scenario in the UAE, the selected study region, as shown in Figure 3(a) (Mwafy and Almorad 2019, Joseph et al. 2022). It is worth noting that the mean of the selected eleven long period records is comparable to the average of twenty seismic input ground motions taken in previous vulnerability assessment results (Joseph et al. 2022). By comparing the fragility functions obtained from the incremental dynamic analysis (IDA) results of the pre-code building with its FRP composite alternatives, valuable information can be gained about the structures' seismic response under increasing levels of earthquake intensity. The analysis carried out in the study uses several local and global damage indices along with a selected ground motion intensity measure (IM) to provide insights into the structures' behavior.

![Figure 3. Fragility analysis results and considered seismic events: (a) Probabilistic functions of the low-rise building and strengthened alternatives; and (b) response spectra of long period seismic events.](image)

The maximum story drift is taken as the global damage index in recent seismic loss estimation studies; hence, the same is considered in this brief research (Mwafy and Almorad 2019, Joseph et al. 2022). The performance limit states for developing fragility curves are selected based on the recommendations of the abovementioned studies. In addition, the current research selected PGA as the intensity measure (IM) as it co-relates seismic demands to applied accelerations and has been utilized in previous studies to describe ground motion severity and compute seismic hazard effectively with practical considerations (Mwafy and Elkholy 2017, Mwafy and Almorad 2019, Joseph et al. 2022). The fragility relationships obtained from this study as illustrated in Figure 3(b) reveal that the low-rise pre-code reference framing system reveals a higher probability of exceeding the limit state in comparison to the composite strengthened buildings, particularly under the long period seismic events at critical limit states. Furthermore, the present study uses the recommendations of damage states as mentioned in previous studies (Joseph et al. 2022). As shown in Figure 4(a), the pre-code low-rise and retrofitted structures’ damage state probabilities (DSPs) were assessed at three earthquake intensity levels that are multiples of the design PGA of the region (Joseph et al. 2022). As observed from Figure 4(a), there is a slight improvement in using the composite retrofit system at the continued occupancy (CO) state particularly at the design seismic level. Complimentary results were observed at one and half times the design seismic level in which the mitigation technique improved the DSP at CO. The seismic strengthening solutions were effective in prolonging occurrence of structural damage, as evidenced by the drastic reductions in...
DSP at structural damage and structural collapse damage states. The PBO composite showed marginally improved seismic behavior compared to the carbon-based composite system specifically at high seismic intensity. At the maximum intensity level, the DSP at structural collapse condition mitigated by 45.5% and 31.5% through the PBO and carbon composite systems, respectively.

5 ASSESSMENT OF RETROFIT EFFECTIVENESS AND COST IMPLICATIONS

The fragility analysis results indicate that it is necessary to evaluate the retrofit measures used through a quantitative ranking approach. To accomplish this, two indices have been employed in this study - the seismic performance index (SPI) and the performance-to-cost index (PCI). The SPI evaluates the seismic performance by calculating the median GMI at various limit states while accounting for the data dispersion in relation to its mean at each limit state through a weighting factor. On the other hand, the PCI assesses the cost implications of the retrofit measures. Moreover, the total material cost and SPI were considered to determine the PCI of the retrofit solutions implemented. Figure 4(b) depicts the calculated SPI and corresponding PCI values for the selected retrofit alternatives. According to the presented results, the P-FRCM retrofit only exhibits 3.6% higher SPI than the carbon composite system, when subject to the long-period seismic events. Contrarily, as illustrated in Figure 4(b), the PCI of the carbon composite method demonstrated a 45% increase compared to the P-FRCM retrofit approach. This substantial variation in PCI primarily revolves around the lesser carbon composite material cost while still exhibiting a similar seismic behavior to that of its alternative. Although the PBO composite demonstrated marginally improved seismic performance for the MRF building, the PCI highlighted that the carbon composite has a better performance-cost ratio.

![Figure 4](image-url)

Figure 4. (a) Damage state assessment results, and (b) prioritization of seismic risk mitigation approaches based on relative seismic capacity and economic considerations.

6 CONCLUSIONS

This study summarized a numerical investigation to assess the impact of retrofitting RC substandard MRF structures using different FRCM composites. Verified fiber-based numerical models were employed to evaluate the performance of a reference RC building before and after the retrofit using SPAs and IDAs and select the most effective FRCM retrofit material. The use of spike anchors in applying the FRCM retrofit approaches to the benchmark structure generated a substantial improvement in its flexural performance and ductility, with an average increase of 53% and 41%, respectively. The retrofit approaches of PBO and carbon retrofit composite also
enhanced the flexural overstrength ratio of the substandard structure by 48% and 33%, respectively. The retrofit measures were effective in delaying the local failure criteria, particularly column concrete crushing and rebar buckling. While PBO composite has better mechanical properties than carbon, it only improved the seismic performance index (SPI) of the strengthened framing system by 3.6% compared to the other alternative. By considering cost and seismic performance, it was concluded that carbon composite is an effective and optimal seismic risk mitigation measure for improving the seismic performance of the reference low-rise structure.

Acknowledgments
This work was supported by the United Arab Emirates University under research grants 31N320 and 31N394.

References
ACI Committee 549, ACI-549.4R-13, Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures, American Concrete Institute, Farmington Hills, MI, USA, December, 2013.


Trapko, T., Urbuńska, D., and Kamiński, M., Shear Strengthening of Reinforced Concrete Beams with PBO-FRCM Composites, Composites Part B: Engineering, Elsevier, 80, 63-72, October, 2015.