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# Seismic performance of non-invasive single brace made of steel and shape memory alloy for retrofit of gravity load designed sub-assemblages

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ABSTRACT

A large stock of existing reinforced concrete structures, even those located in seismic zones, is poorly designed or in-adequately detailed. Such structures are extremely vulnerable during earthquakes and therefore, those structures require immediate intervention in terms of providing retrofit strategies which are adequate, easy to implement and cause minimum disruption. Single bracing system is found to be a promising strategy possessing the qualities mentioned above. In the present study, the load transfer mechanism in the beam-column sub-assemblage due to adoption of single brace system is established. Analytical studies are carried out to understand the influence of geometry and disposition of the single bracing on the reduction of demand in weak joint rezone. Many parameters such as hysteretic behaviour, energy dissipation, material non-linearity, local stiffness distribution etc. which are important to check the efficacy of any retrofit strategy under seismic loading, can not be accommodated in the analytical model. In view of this, experimentally validated non-linear finite element models are developed in the present study. Numerical investigations are carried out using the validated FE models with different types of steel bracing. The study reveals that a properly designed steel bracing can provide significant improvement in seismic performance, for example, 4 times in energy dissipation and 60–80% improvement in strength degradation with respect to the gravity load designed structure. It also indicates that a super-elastic material like shape memory alloy (SMA) with extraordinary properties would be an excellent candidate for usage as bracing. Hence, the effectiveness of nickel-titanium SMA for seismic retrofit of the beam-column sub-assemblage is also investigated and found to be very efficient and better than that of steel bracing.



## 1. Introduction

The infrastructure sector plays an important role on the economic health and social development of any country. Adequate and quality infrastructure is essential for sustainable growth and industrialization. Earthquakes are natural events that often lead to catastrophic consequences and economic losses. Several studies have highlighted that seismic events represent the most important threat to public security and safety. The structures built before 1970s were designed without considering seismic loads and proper detailing. Existence of the 'gravity load based design' structures still dominates the structural world. Catastrophic failure of those structures during the earthquakes highlighted the alarming safety levels of existing buildings. The understanding on nature and consequences of earthquakes is constantly improving and, therefore, the seismic demands imposed on structures are revised frequently, to meet the increased demand. Therefore, the existing structures which were analyzed, designed and detailed as per the available knowledge and prevailing recommendations of previous codes, are to be evaluated for their seismic performance. According to an estimate, one dollar spent on hazard mitigation will result in for four dollars in savings for the society. Obviously, upon assessing the condition of structures and demands in the region, retrofit strategies need to be formulated to increase stiffness, strength, and to achieve desired failure-deformation. The choice of the most suitable and cost-effective strategy for each retrofit is a major challenge for structural engineers.

Various techniques are being explored for developing innovative retrofitting strategy. Pre- and post- earthquake response of

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**Nomenclature**

| | |
|---|---|
| $A_B$ | area of cross section of the beam |
| $A_{br}$ | cross sectional area of the bracing member in the haunch system |
| $A_C$ | area of cross section of the column |
| $D_B$ | length of the beam in the beam-column sub-assembly |
| $D_C$ | height of the column in the beam-column sub-assembly |
| $E_B$ | elastic modulus of the beam |
| $E_{br}$ | elastic modulus of the bracing member in the haunch system |
| $E_C$ | elastic modulus of the column |
| $H_C$ | height of the column in the beam-column sub-assemblage |
| $H'$ | distance of haunch point from beam face (along column height) |
| $I_B$ | moment of inertia of the beam |
| $l_{br}$ | length of the bracing member in the haunch system |
| $I_C$ | moment of inertia of the column |
| $L'$ | distance of haunch point from column face (along beam length) |
| $M_{B,x}$ | moment at a distance × from the joint face towards the beam (within the haunch region) |
| $M_{B,jt}$ | moment at joint face towards the beam |
| $V_B$ | shear at beam end |
| $\alpha$ | inclination angle of the bracing with respect to the beam axis |

the reinforced concrete beam column joints and the performance of the retrofitted joints was studied by Tsonos [1]. Various types of retrofit schemes such as reinforced concrete jacketing, CFRP strips and CFRP wrap were employed. It was brought out that the retrofit schemes increased the shear capacity of the joints and the hinge could be successfully shifted in the beam region. Karayannis et al. [2] proposed a retrofit concept for seismically damaged exterior beam–column joints using reinforced concrete (RC) jacket. Steel reinforced concrete jacket was reported to be very effective. Di Ludovico et al. [3] had effectively used the Fiber-reinforced polymer (FRP). Nonlinear static pushover analysis was performed to evaluate the shear capacity of the retrofitted structure and the experimental results proved the efficacy of the retrofit system An experimental study was carried out by Trung et al. [4] to evaluate the performance of shear strengthened beam-column joint. Various types of retrofit using CFRP in L shape, T shape and X shape and also CFRP strips were provided to retrofit the deficient beam-column specimens. The retrofitted specimens were subjected to reverse cyclic loading to check their efficacies and the X-shape wrapping is found to be most suitable in improvement in the lateral strength and ductility.

Ferro-cement laminates made of high strength cementitious matrices were developed by Shannag et al. [5] for repair/retrofit of deficient of damaged structures. Upon obtaining the promising results from concrete specimens, it was envisaged that welded wire mesh reinforcement in the developed laminates can be a promising material for seismic retrofit of concrete structures. Bedirhanoglu et al. [6] developed the prefabricated high-performance fiber-reinforced cementitious composite panels for seismic retrofit of deficient reinforced concrete structures. It is reported that with proper anchorage, the panels were able to provide improved strength and deformation capacity. Classical theory of mechanics using strut and tie models was employed to calculate the load-displacement of the retrofitted sub-assemblages. For seismic retrofit of existing reinforced concrete (RC) structures, Li et al. [7] used the ferro-cement jackets in the interior beam-column joints. To provide the adequate ductility to the system and to reduce the force transfer to the joint, diagonal reinforcement was adopted. The retrofitting scheme was found to provide improved strength and ductility. Carbon FRP retrofitted beam-column sub-assemblages were experimentally tested by Singh et al. [8] where the CFRP was initially stressed. It was found that both strength and stiffness were improved in the retrofitted structures. However, the long-term durability of the FRP-to-concrete interface in aggressive environments was investigated by Amidi and Wang [9] and severe deterioration of the interface induced by the moisture was observed. An innovative strain hardening cementitious composite (SHCC) reinforced with CFRP laminates was developed by Esmaeeli et al. [10] for repairing the beam-column joints. Damaged beam column joints were repaired using two strategies (only on both faces and jacketing). Seismic performance of the repaired beam-column joints in terms of hysteretic behaviour, dissipated energy, stiffness degradation and ductility were evaluated and promising seismic performance of the specimens was reported. Further, near surface mounted (NSM) FRP was also used [11–13] to effectively utilize the FRP in seismic retrofitting of deficient or deteriorated structures.

A noninvasive retrofit strategy for the deficient reinforced concrete beam column joints was proposed in [14] using a haunch in form of steel bracing at both sides of beam. It was brought out that both was bracing fixed to top and bottom side of the column to the beam is able to divert the force through the bracing, resulting in reduction in moment demand at joint face. For seismic upgrade of existing reinforced concrete (RC) structures, De Matteis et al. [15] used steel and aluminium shear panels as the fuse. Experimental and numerical investigations confirmed the efficiencies of the proposed metal shear panels. Yen and Chien [16] rehabilitated the deficient beam-column joints using the steel plate, and performed experimental and numerical studies to establish the rehabilitation strategy. It was reported that the properly anchored steel plate or steel strips in the beam-column joint was able to exhibit better seismic performance in terms of strength and ductility. Sharbatdar et al. [17] proposed the steel prop technique for seismic retrofit of the shear deficient beam-column joint. It was found that the plastic hinge was successfully shifted to the beam region, ensuring safe failure mode. Mahrenholtz et al. [18] proposed a new upgrade concept exploiting the advantages of prefabricated steel bracing. Buckling-restrained braces (BRBs) with post-installed anchors were employed to retrofit the damaged reinforced concrete frames and significant improvement in the responses was observed. The retrofit scheme was found to provide more strength and energy dissipation. Performance based design of low-rise structures protected with Buckling-Restrained Braces (BRBs) was proposed by Guerrero et al. [19]. The retrofit strategy was designed to provide two SDOF systems with different deformation capabilities. The strategy provides alternate mechanism to yield and exhibited a safe failure mode.

Besides the experimental attempts which are found to expensive, time consuming, and size-, material- and scheme- specific, computational models are developed and numerical studies are carried out by various researchers to evaluate the nonlinear performance of structures/components under cyclic loading. These models can be used as tools for design of retrofit as well. Performance evaluation and strengthening of deficient beam-column sub-