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Seismic performance of ordinary RC frames retrofitted at joints by FRP sheets

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ABSTRACT

This paper reports on the results of an investigation into the effectiveness of FRP retrofitting the joints in enhancing the seismic performance level and the seismic behaviour factor (*R*) of ordinary RC frames. The flexural stiffness of FRP retrofitted joints of the frame is first determined using nonlinear analyses of detailed FE models of RC-joint–FRP composite. The retrofitted joint stiffness is then implemented into the FE model of the frame in order to carry out nonlinear static (pushover) analyses on the FRP retrofitted frame. The seismic performance level and *R*-factor components of the retrofitted frame are then compared with those of the original frame and the same frame retrofitted with steel bracings, reported previously. The results show that the performance level and the seismic behaviour factor of the FRP retrofitted RC frame are significantly enhanced in comparison with the original frame and are comparable with those of the steel-braced frame. It is also found that using FRP at joints may upgrade an ordinary RC frame to an intermediate and even a high ductility frame.

1. Introduction

The use of FRP sheets to create composite concrete structures has increased in recent years. This is particularly true for seismic upgrading of existing reinforced concrete (RC) structures, many of which were designed for gravity loads only or according to the old codes of practice. FRP materials have several advantages over steel: they are lightweight with superior strength and stiffness-to-weight ratios, they have a relatively high corrosion resistance, and FRP sheets can be moulded to concrete surfaces. The seismic retrofit strategy for an RC frame may include strengthening deficient members such as beams, columns and beam–column joints to increase strength, stiffness and/or ductility and to enhance the overall seismic performance of the frame by increasing lateral strength, reducing drift and/or increasing ductility. In the last decade, a vast amount of research has been carried out on the FRP retrofit of RC frame members, such as beams [1–7] and columns [7–12], all indicating the effectiveness of the retrofit technique and some highlighting certain problems associated with the technique including brittle debonding failure and the methods to overcome these problems [13–15].

Beam–column joints are also crucial components of a frame both in terms of structural stability and its seismic performance. In a numerical study, Parvin and Granata [16] showed that when joints of an RC frame were reinforced with FRP laminates, the moment capacity was increased by around 37%. Antonopoulos and Triantafillou [14] developed analytical models for the analysis of RC joints strengthened by FRP strips or fabric. Their models provide equations for stresses and strains at various stages of the response to failure by either concrete crushing or FRP fracture or debonding. They concluded that the effectiveness of the FRP retrofitting scheme increases considerably if debonding is suppressed and depends heavily on the distribution of layers in the beams and columns. Li et al. [17] conducted both experimental and numerical studies on the behaviour of concrete beam–column connections reinforced with hybrid FRP sheets. Their analysis results showed that the designed hybrid FRP reinforcement greatly improves the stiffness and load carrying capacity of the joint; it also delays the crack initiation at the joint through FRP confinement. Mahini and Ronagh [18] used web-bonded FRP sheets for strengthening of exterior beam–column joints. They tested the effectiveness of web-bonded CFRP on energy absorption capacity of 1/2.2 scale

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RC joints, in order to evaluate the possibility of relocating the plastic hinge away from the column face. Their experimental studies showed that the FRP repairing/retrofitting system can restore/upgrade the integrity of the joint, keeping/upgrading its strength, stiffness and ductility, as well as, shifting the plastic hinge from the column facing further into the beam, in such a way that the joint remains elastic. The practicality and effectiveness of using web-bonded FRPs on plastic hinge relocation has also been reported by Smith and Shrestha [19]. In another study, Mostofinejad and Talaeitaba [20] proposed a finite element model for the nonlinear analysis of RC joints covered with FRP overlays. Their results showed that good ductility and improved strength are achieved by employing appropriate FRP sheets.

Despite the large amount of research conducted on the behaviour of different RC frame components retrofitted with FRP, little research has been carried out on the behaviour of FRP retrofitted RC frames. In an experimental study, Balsamo et al. [21] evaluated the seismic behaviour of a full-scale RC frame repaired using CFRP laminates. They indicated that the repaired frame had a large displacement capacity without exhibiting any loss of strength, while providing almost the same energy dissipation of the original frame. In another experimental study Di Ludovico et al. [22] carried out bi-directional seismic tests on an under-designed, full-scale RC frame and repeated the tests on the same frame after retrofitting it at joints and columns by FRP. Their experimental results showed the effectiveness of the FRP retrofitted configuration in improving the global performance of the structure in terms of ductility and energy dissipation capacity and enhancing its load capacity by 50%. In a numerical study, Zou et al. [23] presented an optimization technique for the performance-based seismic FRP retrofit design of RC building frames. Their numerical studies showed that the seismic resistance of an RC frame designed for gravity loads only can be substantially enhanced through confinement of columns using FRP jackets. They indicated that FRP confinement increases the strength of columns but has little effect on their stiffness, which is an important advantage in seismic retrofit, as larger stiffness lead to higher seismic forces. In a recent study, Niroomandi and Maheri [24] also studied the effects of FRP retrofitting the joints on improving structural ductility of ordinary RC frames.

The main objective of the current study is to investigate the effects of strengthening the joints by FRP sheets on the seismic performance level and the seismic behaviour factor (R) parameters of ordinary RC frames. The retrofit scheme considered here is the CFRP web-bonding of the frame joints. The full web-bonding of the beam considered is similar to the scheme used previously by a number of investigators including those reported in [13,14,16,20,25]. The scheme does not allow for the presence of an integrated RC slab. It, however, can be used for RC frames supporting non-integrated composite slabs and roofs as well as frames with integrated RC slabs having low slab–beam thickness ratios. The seismic performance level and R-factor components including the ductility reduction factor and the over-strength factor are extracted from nonlinear static (pushover) analyses of the frame. The nonlinear pushover analysis is known to represent well the seismic performance of structures. Di Ludovico et al. [22] carried out pushover analysis on the numerical models of the FRP retrofitted frame they tested under bi-directional seismic loading and obtained results close to the experimental results, indicating the effectiveness of the nonlinear pushover analysis.

In this paper, a two-dimensional, eight-storey, three-bay, existing RC moment resisting frame, which was retrofitted by Maheri and Akbari [26] using a steel bracing system, is retrofitted again at joints with web-bonded CFRP sheets and the results of nonlinear pushover analyses are compared with those of the original frame and the steel-braced frame. The retrofitted joints stiffness in the form of moment–rotation relation is first determined in detailed FE modelling of the composite joints and the results are then utilised to carry out nonlinear pushover analysis of the full frame to evaluate its force–displacement capacity curve. The capacity curve is then utilised to evaluate the seismic performance parameters of the frame.

2. Nonlinear finite element analyses of retrofitted joints

Due to complexity of the composite behaviour of FRP and RC members, presenting an appropriate numerical model for the nonlinear analysis of FRP retrofitted joints is of great importance. In the following, such a model is developed using ANSYS software [27] and verified against experimental data provided by Mahini and Ronagh [18]. In the nonlinear finite element model, both geometric nonlinearities and material inelasticity are taken into account. The concrete was modelled using an eight-node solid element, specially designed for concrete material (ANSYS element solid65). This element is capable of handling plasticity, creep, cracking in tension and crushing in compression. As for the failure criterion, the five-parameter William–Varnk model was used. This model is able to account for the cracking of concrete in tension and crushing of concrete in compression; furthermore, it uses a smeared crack model. The longitudinal and transverse reinforcements have been modelled using a series of two-node link elements (ANSYS element link8). The FRP sheet is also modelled using an eight-node three-dimensional multi-layered solid element (ANSYS element solid45). This element has translational stiffness but no bending stiffness. It also uses an anisotropic material. The material uses a bilinear stress–strain curve in both compression and tension and in any of the Cartesian directions. Although FRP material is linear elastic, a number of investigators have reported that the above-described solid45 element is the most suitable element in the ANSYS software to model the behaviour of FRP [16,20]. A control on the maximum stresses in the FRP material obtained in the present study shows, however, that the FRP material did not reach the specified yield point in the bilinear model and it had indeed remained linear elastic throughout. To perform the nonlinear analysis, the load was applied step by step and the modified Newton–Raphson method was used for the solution.

To eliminate the problem of debonding of FRP laminates in the FE analysis, i.e., the effects of local failure due to shear or normal stress concentrations at the end of the laminates, the maximum strain in FRP sheets was checked to ensure that it is less than the limiting quantities suggested by ACI 440.2-2008 [28]. The ACI 440.2 adopts a model for FRP debonding which is similar to the one proposed by Chen and Teng [29] and Teng et al. [30]. The model limits the effective strain in the FRP laminate to prevent the intermediate crack induced debonding failure mode. The limiting value for the effective FRP strain is given by:

$$\varepsilon_{fd} = 0.41\sqrt{\frac{f_c'}{n.E_f.t_f}} \leq 0.9\varepsilon_{fu} \quad (1)$$

where, ε_{fd} is the maximum strain allowed in the FRP laminate to prevent debonding, f_c' is the 28 days standard concrete cylinder compressive strength, E_f and t_f are the elastic modulus and the thickness of the FRP laminate, respectively and n is the number of laminate layers. A full review of bond strength of FRP laminates to concrete may be found in the state-of-the-art review presented by Sayed-Ahmed et al. [31].

To verify the accuracy of the numerical model, an experimental study conducted on a retrofitted exterior RC joint by Mahini and Ronagh [18] was selected. The retrofitted joint tested by Mahini and Ronagh is shown in Fig. 1. Characteristics of FRP sheets used