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Study on Effect of FRP Reinforced Manners on Seismic Performance of Concrete Frame Structure

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Abstract Many studies showed that FRP bonded to the concrete beams and column surface can effectively enhance the mechanical properties of members, and FRP reasonably bonded to the beam-column joint area can significantly improve the seismic performance, but not enough studies have been carried out on the overall mechanical properties in structure after the framework members are partially covered with FRP. In this Paper, based on the seismic demand analysis of the concrete frame structure, as well as FRP seismic enforcement strategy, a fiber attachment method has been proposed for FRP seismic reinforcement framework. Taking a two-layer dual-span plane framework as an example, nonlinear static analysis has been carried out on FRP-reinforced framework, the capacity spectrum method has been adopted to assess the seismic performance of reinforced framework and the impact of different FRP-reinforced methods on structural seismic performance has been discussed. The results showed that the method of moderate shear-resistance reinforcement in the joint core area, as well as the beam-column plastic hinge area, can effectively improve the seismic performance of the framework, the application of GFRP reinforcement features higher cost-performance ratio, and the FRP bonding at ± 45º in the joint core area can better the reinforcement effect.

Keywords: Reinforcement, reinforced concrete frame, FRP, seismic performance

Introduction

According to many studies in recent years, the effectiveness of the technique attaching FRP sheets on the surface of reinforced concrete structure as reinforcement have been proved (Ye and Feng 2006, Zou et al. 2007, Balsamo et al. 2005), which has been widely used in the engineering practices. At present, most studies focus on the evaluation and analysis of the effect on FRP reinforcement in the individual members, the design of the engineering reinforcement also starts from the requirement of the bearing capacity of partial or individual members to provide the directional reinforcement for the areas with insufficient capacity, and even the improvement of ductility is considered, it also mainly starts from the aspect of concept design. While better seismic performance of the integral reinforced concrete structure should be realized by the composition of the members as well as the reasonable matching of all members on their bearing capacity, rigidity and ductility, so as to create a reasonable damage form, for which it is required to make deep study on the integral working performance of the FRP reinforced concrete members. However, there is not enough study done in this respect currently.

The study result of the individual members of the frame structure showed that, the beam and floor of the bending members would be improved with their bearing capacity under the vertical load but with lower ductility after they were attached with FRP in their tensile regions; FRP reinforced frame column would be obviously improved in their shear strength and ductility under axial force and horizontal cyclic load; and the composite unit of beam-column joints may be effectively improved with its seismic performance if it is reinforced with reasonable FRP attachment. For analysis on integral reinforcement of frame structure for earthquake resistance, it is firstly required to determine the reasonable and effective FRP attachment methods, secondly achieve correct understanding of and analysis on the bearing capacity, rigidity and deterioration of frame structures after reinforcement, and finally carry out reasonable evaluation on the overall seismic performance of the structures, to find out the relatively economical reinforcement methods with high efficiency. The study or solution on the above problems represents relatively great theoretical significance and engineering practice value.

FRP Seismic Reinforcement Method for Concrete Framework

Strategy for Structural Seismic Reinforcement The seismic reinforcement of existing structures shall generally reinforce the partial members based on the shortcomings from the visible injuries of the structural members or the overall theoretical analysis of the structure, namely, to appropriately strengthen and improve the individual members which may affect seismic performance, with the specific measures as follows (Balsamo et al. 2005): (1) increase of ductility of members already characterized by flexural collapse; (2) modification of collapse mode of members from shear (brittle) to flexure (ductile); (3) increase of column strength capacity in order to modify the hierarchy of strength of the structure. The first action can be performed by increasing the constraint level of members in order to increase the strain capacity of concrete and fully exploit the steel yielding. The second action can be performed by increasing the shear strength of the element in order to make it larger than the flexural capacity at yielding and then avoid brittle behaviors. The last action can be carried out by increasing the strength of some members (i.e., columns and joints); in this way, the failure of others (i.e., beams) occurs before and then prevents that of the upgraded members. This third choice allows protecting those members whose failure could be critical from a global standpoint and then improving the seismic behavior of the structure.

No matter what method is adopted, the seismic reinforcement shall ultimately aim at the transformation of the structure into a seismic structural system featuring appropriate expansivity and energy dissipation mechanism.

FRP Seismic Reinforcement Method Compared with the traditional methods of cross-section expansion and steel coating, FRP reinforcement method can achieve the coordination with the original structure more easily, featuring no weight increase of the structure and no impact on the construction space and aesthetics, but good durability. Besides, as long as the structural expansivity and energy dissipation capacity are effectively enhanced by means of appropriate enforcement methods, the goal of anti-seismic reinforcement can be achieved.

The framework anti-seismic performance depends on the expansivity and energy dissipation capacity, based on sufficient bearing capacity and lateral rigidity, while the plastic hinge rotation and development capacity will to some extent determine the overall expansivity and energy dissipation capacity of the framework and the proper reinforcement at the potential plastic hinge can achieve the goal of anti-seismic reinforcement. The framework beam and column ends belong to the potential locations of structural plastic hinges, and its reinforcement shall also avoid changing the structural failure mechanism, and the framework anti-seismic performance can thus be more effectively enhanced only if the principle of “Strong column-weak beam and strong shear-weak bending” is followed.

The author of this Paper proposed the beam-column FRP reinforcement scheme and concrete design methods for the beam-column combination, and such methods have been proved effective based on experiments and research, with the details shown in references (Peng et al. 2006). If possible (non-middle-tier intermediate joints), the joint core area shall apply shear reinforcement covered with FRP at first, and then the L-shaped bend-resistance fiber strips shall be applied at the beam column end, which shall in the end be treated with shear reinforcement with the aforementioned fibers anchored. Such beam-column joint specimens reinforced in this way have experienced the seismic tests in the low-cycle repeated loads, which proved that: the FRP reinforced beam-column joint combination features significant increase of weight-bearing capacity, the coated fiber at the joint core area is characterized by bounding function, which can directly improve the weight-bearing capacity of the joint, and the bend-resistance fiber strips bounded to the beam-column end can partially share the bending moment, reduce the stress of longitudinal reinforcement, thus reduce the shear of the incoming joint, and indirectly enhance the weight-bearing capacity of the joint.

This Paper adopts the above-mentioned FRP reinforcement method to reinforce the two-layer dual-span concrete framework, and carries the comparative analysis of seismic performance before and after the reinforcement.

FRP Seismic Performance Analysis of the Reinforced Concrete Framework

Analysis Models of FRP Reinforcement Frame Structure The test model of two-layer two-span frame shown in Fig. 1 is taken for analysis, with the section of the middle beam in the frame 150mm×250mm, two 12mm longitudinal reinforced bars (HRB335) respectively at the upper and lower parts, with the column section 150mm×180mm, and three 12mm longitudinal reinforced bars (HRB335) respectively at both sides of the column along the frame, and it was placed with C20 concrete. Every joint in the frame is reinforced with FRP, for which the attachment method of fiber strengthening is as shown in Fig. 1 above, where the fiber strip 1 for the middle joint is horizontally attached at both sides of the joint. The unstrengthened frame is numbered as KJ-1, the frame reinforced by means of GFRP and CFRP inter-layer mixture is numbered as HRKJ, and the difference between HRKJ-1 and HRKJ-2 is that the former features the horizontal fiber strips affixed to the joint core area, while the latter the direction of ± 45º.

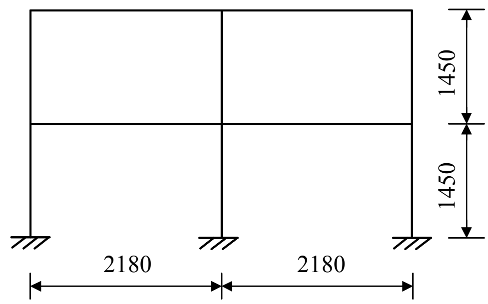

Figure 1: Schematic diagram for frame

SAP2000 V14 software is used for the Pushover static elastoplastic analysis, in which the modeling is based upon the frame pole unit, the constitutive relations of concrete and reinforced bars followed the regulations in the GB50010-2002 specifications, and the measured results in the test of joints are applied to define the relations between bending moment and curvature[4]. The M3 plastic hinges were designed at the beam ends, that is, taking no consideration of the influence of axial force on the bending resistance of the section; and PMM plastic hinges were designed at the column ends.

The progressive loading model from the frame top is used with 0.15g, which is designed as the basic acceleration during analysis.

Analysis Results and Seismic Performance Evaluation For capacity spectrum method, the Pushover analysis is made on the structure to obtain the relation curve between shearing strength and the displacement of control point, and transform the curve to find out the capacity spectrum curve, in which longitudinal coordinate is taken as acceleration spectrum and horizontal coordinate as displacement spectrum, the designed response spectrum under the damping ratio corresponding to the predicted maximum displacement response is used to express the earthquake demand curve of the structure, while the displacement corresponding to the intersection point of capacity spectrum curve and the demand curve is the required target displacement. Capacity spectrum method is based upon displacement performance. Since the software SAP2000 integrates demand spectra of ATC-40, it can be applied to current specifications in China through parameter transformation, and can automatically transform the curves obtained from Pushover analysis into the capacity spectrum, based on which the performance point (target displacement) will be automatically solved from the equivalentization of standard demand spectrum.

The displacement performance point analyzed in the frame of this Paper is shown as in Figure 2, and the frame target displacement and its comparative analysis refers to Table 1.

From analysis of the results in Table 1, it can be seen that all the inter-layer displacement angles corresponding to the target displacement of various reinforcement frames were smaller than 1/50, complying with the requirements in current specification GB50011-2001 for earthquake resistance and meeting the requirements of maximum deformation in earthquake. The allowable value of inter-layer displacement angles in the unstrengthened frame is 1/50, which means that the frames show insufficient reserve of ductility, and that target displacement is larger than the ultimate displacement. Target displacement at the dropping section of Pushover curve means the presence of the yielding member in the frame structure, and cannot meet the demand on its ductility in case of earthquake with fortification intensity for the rarely happening earthquake, when the frame should be reinforcement for earthquake resistance so as to improve its ductility. All the inter-layer displacement angles of frames reinforced with various FRP are far less than 1, and all the target displacements are smaller than the ultimate displacement, the capacity demand ratio parameter d/D is far less than 1, which is only 45.8% in GRKJ-1, which means the reinforcement frame maintained relatively large reserve of ductility under such earthquake intensity with fortification, and showed good seismic performance.

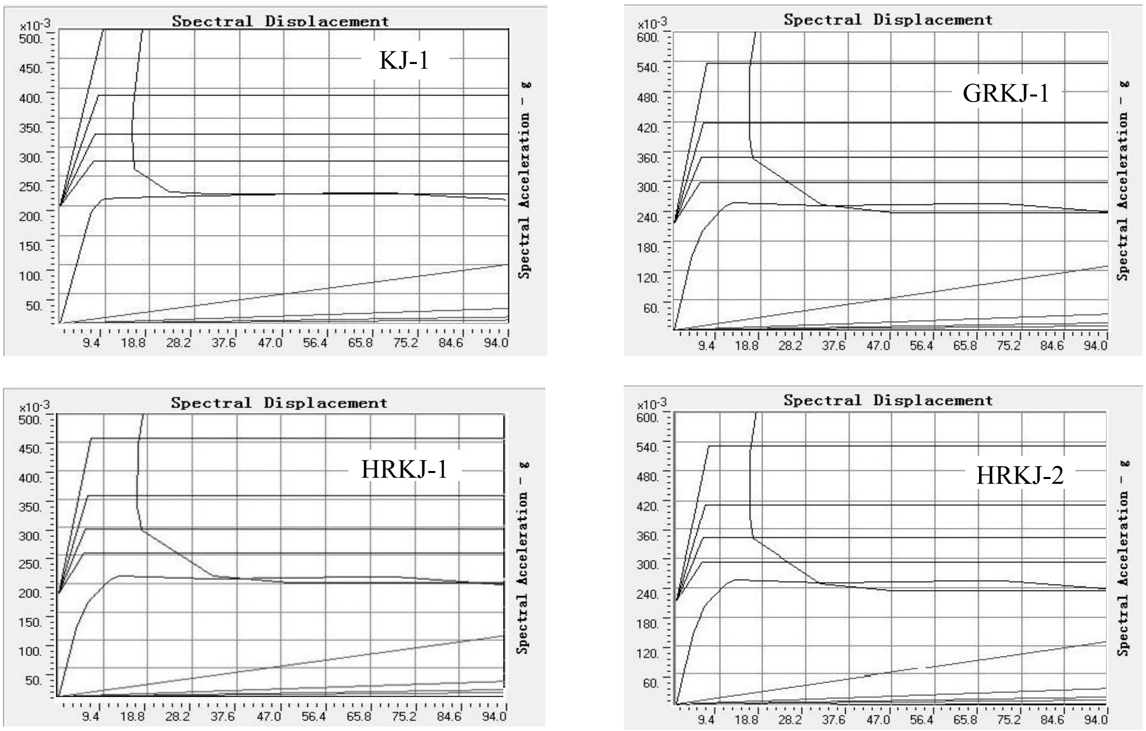

Figure 2: Performance points of frame displacement in analysis with capacity spectrum method

Table 1: Analysis on target displacement of frames

Item No.	*Target displacement d (*mm*)*	*Interlayer displacement angle*	*Ultimate displacement D(*mm*)*	*d/D*
KJ-1	57.2	1/51	55	> 1
GRKJ-1	36.6	1/79	80	45.8%
HRKJ-1	41.9	1/69	72	58.2%
HRKJ-2	38.6	1/75	77	50.1%

Impact Analysis of FRP Reinforcement Methods on the Framework Seismic Performance

Fiber Varieties The reinforced fibers commonly used in engineering mainly include CFRP and GFRP, etc., and CFRP mainly features high tensile strength and elastic modulus, but low extension rate and high price; GFRP features slightly lower tensile strength and elastic modulus, but higher extension rate and low price. In concrete structural seismic reinforcement, many scholars believe that based on the same stiffness, the use of GFRP shall have better overall efficiency than CFRP (Amoury and Ghobarah 2002, Ou et al. 2003), but CFRP features high-strength performance, superior durability and corrosion resistance, which has enabled the current domestic reinforcement engineering applications to prefer CFRP, and in fact, the two kinds of fibers mixed in accordance with the appropriate ratio will better its effect (Li et al. 2002, Costas et al. 2003). The composite material with more than two kinds of continuous fibers bounded on the concrete framework surface is called HFRP, and the HRKJ-1 and HRKJ-2 members in this Paper are based on this approach.

The push-over curve calculated in this Paper refers to Figure 3, in the calculation the frame top layer is adopted as loading control point, and the limit displacement is set at the point of significant drop on Push-over curve.

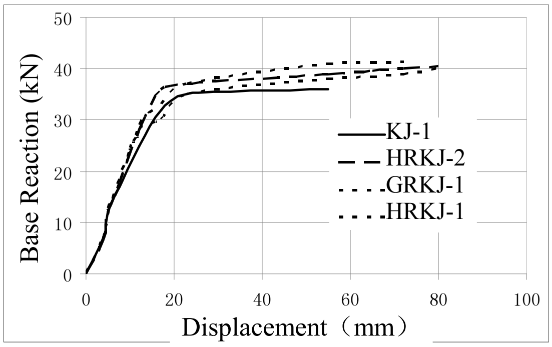

Figure 3: Comparison of push-over curves for the frames

The limit deformation capacity of HRKJ-2 features the largest increase of about 45% compared with the non-reinforced framework KJ-1, and the limit deformation capacity of RKJ-1 and HRKJ-1 is increased by 44% and 32%. The different FRP reinforcement methods may be characterized by different enhancement of the reinforcement limit weight-bearing capacity, but the difference is not too obvious. It showed that among the reinforcement methods adopted in this Paper, GFRP and HFRP both had fairly good effect of reinforcement, but GFRP of relatively low cost featured good cost-effective ratio. HFRP can also achieve the expected reinforcement, but its hybrid effect is not easily seen.

FRP Attachment Direction Currently, the domestic reinforcement engineering is using such FRP continuous fibers mostly of one-way performance, and if the relatively optimized reinforcing effect is to be achieved, the fibers shall be applied along the direction of stress control to the best. The seismic reinforcement of concrete framework members shall mainly follow the constraint theory, namely, the outer cover of FRP shall be adopted to enable the internal concrete to form certain constraint effects so as to enhance the weight-bearing capacity and ductility of the concrete members and structures and improve their seismic performance. The column reinforcement may easily achieve good constraint effect, and the unidirectional FRP affixed along the hoop reinforcement can significantly enhance the reinforcing effect. Due to the impact of the floor, the binding effect resulting from the U-shaped FRP affixed along the hoop reinforcement on end concrete mainly depends on the interfacial bond and the anchoring effect between fiber end joints. The concrete in the core area of the joint while in earthquake mainly suffers from the two-way alternating shear effect, and often two diagonal cracks will appear, so bi-directional FRP affixed in the direction of ± 45º shall be adopted, for example, HRKJ-2 in this Paper. From the above analysis result, the seismic performance of HRKJ-2 framework is superior to that of HRKJ-1.

The references (Balsamo et al. 2005) conducted the pseudo-dynamic seismic test of the full-scale CFRP reinforcement concrete framework, with the vertical members of the test framework of two shear walls and two pillars. The reinforcement of the beam-column wall joint in the test adopted two-way (0º - 90º) and four-directional (0º -90º - ± 45º) braided FRP, and the beam ends and columns all adopted one-way FRP reinforcement. The test members were finally destroyed due to FRP failures of the column and wall bases, and the partial framework above the bases was not achieved, but the test results showed that the structure with CFRP reinforcement was characterized by a greater displacement capacity, without any reduction of weight-bearing capacity, the cyclic loading performance was stable, without any obvious damage accumulation, the energy dissipation mechanism similar to the original structure could be provided, and the seismic performance featured a certain increase after reinforcement. It indicates that the multi-directional braided fiber reinforcement of the joint core area can achieve a sound reinforcement effect.

Conclusions

Based on seismic need analysis of the concrete frame structure, as well as FRP seismic enforcement strategy, a fiber attachment method has been proposed for FRP seismic reinforcement framework. Taking a two-layer dual-span plane framework as an example, nonlinear static analysis has been carried out on FRP-reinforced framework, the capacity spectrum method has been adopted to assess the seismic performance of reinforced framework and the impact of different FRP-reinforced methods on structural seismic performance has been discussed. Conclusions are drawn as follows:

(1) The method "that the joint core area shall apply shear reinforcement covered with FRP at first, and then the L-shaped bend-resistance fiber strips shall be applied at the beam column end, which shall in the end be treated with shear reinforcement with the aforementioned fibers anchored" can effectively improve the seismic reinforcement performance of the concrete framework.

(2) Different fibers shall feature different reinforcement effects, and GFRP of good ductility shall have good reinforcing effect, with a good cost-effectiveness ratio. HFRP can also achieve the expected reinforcement effect, but the hybrid effect is not easily seen.

(3) The unidirectional FRP shall be affixed along the direction of the beam-column hood reinforcement to achieve a certain constraint effect, the joint core area shall adopt multi-directional braided fiber reinforcement, and especially FRP affixed along the ±45° direction may relatively optimize the seismic reinforcement effect under the premise of firm anchoring.

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