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A State of the Art Review on the Behavior of Reinforced Concrete (RC) Beams under Cyclic Loading

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Abstract

In the last two decades, the study of reinforced concrete (RC) structures elements such as bridge deck slabs, bridge girders, or offshore installations, which are subjected to cyclic action typically induced by seismic motions has received the attention of many researchers. Furthermore, the past two decades have witnessed rapid growth in the use of fiber-reinforced polymer (FRP) confining jackets for the strengthening/retrofit of reinforced concrete (RC) columns and beams. Moreover, several theoretical and empirical models have been proposed for evaluating the shear strength of beams, columns and beam-to-column joints. In this paper, an overview of the models currently available in the scientific literature for evaluating the shear capacity of beams, columns and exterior beam-to-column joints is reported. Further, important practical issues which contribute in shear strengthening of structures with different element types especially RC beams with different strengthening techniques, such as steel plate and FRP laminate are discussed. Finally, directions for future research based on the existing gaps of the existing works are presented.

Keywords

Cyclic Behavior, RC Beams, Shear Strength, Beam-Column Joined, RC Column

1. Introduction

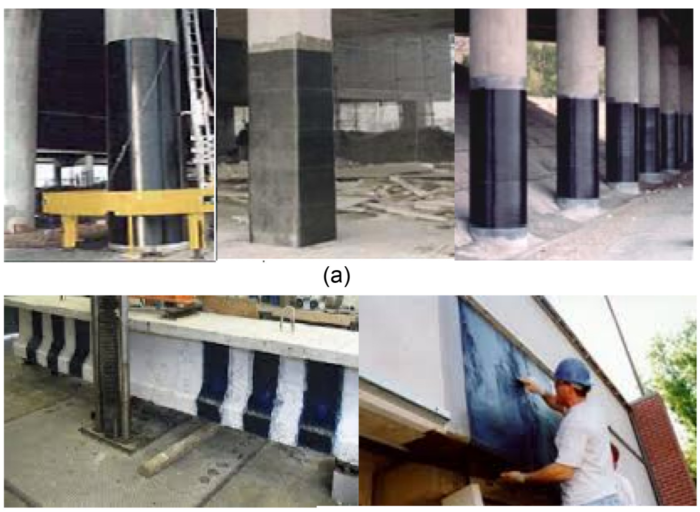
Reinforced concrete (RC) structures are commonly designed to satisfy two criteria: serviceability and safety. To ensure the serviceability requirement, it is necessary to accurately predict the cracking and deflections of RC structures under working loads. The design of reinforced concrete structures is subjected to cyclic loadings such as bridge deck slabs, bridge girders, or offshore installations necessitate the consideration of fatigue. These structures typically experience millions of stress cycles during their service life; the cyclic load can be detrimental to their structural performance [1].

Recently, the study of reinforced concrete structures sections subjected to cyclic action typically induced by seismic motions has received the attention of many researchers. Furthermore, to assess the safety of structures against failure, an accurate estimation of the ultimate load is essential. In particular, to arrive at a complete assessment of the strength, stiffness, and ductility of existing structures and newly designed critical structures such as long-span bridges and tall buildings, a nonlinear dynamic analysis has been strongly required.

The Importance of Structures Repairing and Strengthening

Repairing and retrofitting of existing RC structures represent one of the key issues in modern seismic engineering. Recent earthquakes have repeatedly demonstrated the inadequate protection level toward both damage and collapse of the existing buildings. Given the high economic cost of demolishing and rebuilding under designed structures, the current trend is to recover these structures by improving the flexural and shear strength of some members and increasing their local or global ductility. Application of FRP for columns and beams showed in **Figure 1**.

The past two decades have witnessed rapid growth in the use of fiber-reinforced polymer (FRP) confining jackets for the strengthening/retrofit of reinforced concrete (RC) columns. The three common types of FRP composites for use in column strengthening/retrofit include carbon FRP (CFRP), glass FRP (GFRP), and aramid FRP (AFRP). Conventional FRPs have a linear elastic stress-strain response followed by brittle rupture at a relatively small rupture



(a)

(b)

Figure 1. FRP strengthening of (a) columns (b) beams.

strain typically around or less than 1.5%, 2.5% and 3% for CFRP, GFRP, and AFRP respectively.

2. Previous Experimental Studies

2.1. Reinforced Concrete Beams

Reinforced concrete (RC) beams in general fail in two types: flexural failure and shear failure. As it known well, the shear failure of RC beam is sudden and brittle in nature. It is less predictable and gives no advance warning prior to failure. Shear failure is more dangerous than the flexural failure. It is why the RC beam must be designed to develop its full flexural capacity to assure a ductile flexural failure mode under extreme loading.

The RC beams with a T-section under cyclic loading with the external bonding of carbon fiber reinforced polymer (CFRP) straps were presented by Özgür Anil (2008) [2] [3]. Width of the CFRP straps, arrangements of straps along the shear span, and anchorage techniques considered as main experimental parameters. Results showed that, when strengths of the specimens in experimental program were investigated, the effects of strengthening with CFRP straps on strength were closely related with the arrangements of CFRP straps, concrete strength, and whether anchorages were applied or not. They compared the results suggested by ACI-440 Committee report with the experimental ones.

Hans I. Archundia-Aranda, *et al.* (2013) [4] tested ten prototype simply-supported reinforced concrete beams under cyclic loading to evaluate and confirm the usefulness of a proposed equation for estimate the shear strength of reinforced concrete haunched beams. The cyclic test results also confirmed the usefulness of an empirical equation previously proposed to assess the shear strength of reinforced concrete haunched beams, taking into account parameters such as the haunch angle, the concrete compressive strength, the shear reinforcement and the contribution of the inclined longitudinal reinforcement. An experimental campaign based on four reinforced concrete beams subjected to reverse three-point bending tests was presented by R. Crambuer, *et al.* (2013) [5] to exploring the possibility of identifying a local constitutive model in order to account for damping in a natural way. The multi-fiber approach allows including nonlinear constitutive laws in a finite element model built from Timoshenko's or Euler-Bernoulli's beam elements were used. From the numerical results obtained, it appears that the use of refining constitutive models at the material scale allows decreasing the contribution of the viscous damping matrix drastically.

Hybrid FRP bonded-reinforced concrete beams subjected to quasi-static cyclic loading in an attempt to represent the effect of repetitive loading were presented by Hasan Nikopour, M. Nehdi and P. Broumand (2012) [6]. Many parameters were measured and compared with predictions of a computational model based on finite element analysis. Their Experimental results demonstrated that hybrid applications of FRP sheets could improve the shear performance of retrofitted RC beams and increase the ultimate strain of the FRP sheets at failure. The theoretical results were in reasonable agreement with the corresponding experimental results. The behavior of steel-fibre-reinforced concrete beams under cyclic loads was studied by A. Abbas, S. Syed Mohsin and D. Cotsovos (2012) [7]. They reported that the use of steel fibres could result in a significant reduction in conventional reinforcement without compromising ductility and strength requirements. The investigations provided insight into how the steel fibres can help reduce the amount of conventional shear links. The numerical model was calibrated against existing experimental data to ensure the reliability of its predictions. Parametric studies were subsequently carried out using the full practical range of steel fibre dosages. Sreeja M. D. (2013) [8] studied the behavior of steel fibre reinforced concrete beam under cyclic loading by experimental and theoretical works and described the influence of steel fibre distribution on the ultimate strength of concrete beams. Load-deflection curves, crack load and at ultimate load were established. Finite element models ANSYS was used to validate the experimental investigations with the analytical studies.

Sergio F. Breña, *et al.* (2011) [9] and Kent A. Harries *et al.* (2000) [10] studied experimentally the performance of conventionally reinforced coupling beams subjected to cyclic load. The effect of different amounts of longitudinal reinforcement, shear stiffness and transverse reinforcement on behavior is highlighted as main parameters. The results showed that the evaluation of shear strength equations revealed that existing equations contained in ASCE/SEI 41-06 are not adequate to characterize performance at moderate to high chord-rotation demands because they are independent of displacement ductility. Shear stiffness reduced to approximately 10% of gross stiffness at ductility demands as low as 1.33. The shear performance of RC beams strengthened in shear with externally bonded carbon fiber-reinforced polymer (CFRP) strips subjected to a cyclic loading for two million cycles at 1 Hz is investigated by Sang-Wook Bae *et al.* (2013) [11]. Results obtained from experimental study compared with that in the existing literature and showed that RC beams strengthened in shear with externally bonded CFRP could survive two million cycles of cyclic loading without failure. Moreover, shear strengthening by CFRP strips increased the shear strength by 26.3% compared with the unstrengthened control beam, which confirms the results of many existing studies. Eight simply supported RC beams containg edge opening, with and without repairing were studied by Saad Khalaf Mohaisen, *et al.* (2012) [12] to measure the deflections up to a specific limit below collapse. Results obtained by ANSYS 7.0 program show good agreement with experimental results.

Afsin Canbolat, *et al.* (2005) [13] investigated the seismic behavior of high-performance fiber-reinforced cement composite (HPFRCC) coupling beams. The test results showed that HPFRCC coupling beams with simplified diagonal reinforcement exhibited higher shear strength and stiffness retention. HPFRCC beams with supplemental diagonal bars reached a drift of at least 4.0% while maintaining approximately 80% of their shear-carrying capacity. The effects of transverse steel reinforcement corrosion on the seismic behavior of RC beams designed conforming to the ACI 318 seismic design provisions, and with a moderate shear stress level and an equal amount of tension and compression longitudinal reinforcement were examined experimentally by Yu-Chen Ou, *et al.* (2014) [14] using cyclic loading. Cyclic test results indicated that the beams could sustain a corrosion weight loss of 6% in the hoops and still maintain ductile flexural behavior. They concluded that the amount of corrosion substances filled in the cracks volume was approximately 25% of the reduced volume of steel due to corrosion.

Georges El-Saikaly, *et al.* (2014) [15] examined the fatigue performance of RC beams strengthened in shear using EB-CFRP sheets. The specimens were subjected to fatigue loading up to six million load cycles at a rate of 3 Hz. The results demonstrate the effectiveness of the EB-FRP shear strengthening technique for extending the service life of RC beams under fatigue loading. The presence of transverse steel in retrofitted beams resulted in a substantial gain reduction in shear resistance due to CFRP, confirming thereby the existence of an interaction between internal transverse steel and EB-CFRP. Moreover, the experimental tests on fatigue behavior of the performance steel-fiber-reinforced concrete (SFRC) beams were conducted [16].

Six steel reinforced beams with various transverse reinforcement ratios, engineered cementitious composite (ECC) thicknesses, and shear span-depth ratios were tested under reversed cyclic loading [17]. Experimental results show that the steel reinforced ECC beams show better seismic performance regarding load carrying capacity, shear resistance, energy dissipation capacity and damage tolerance compared with steel reinforced concrete beams. The precast pre-stressed I-beams under three-point bending cyclic loads varying between 60% and 90% of their ultimate moment were tested [18]. Results concluded that cyclic loading caused insignificant variations in beam stiffness and, as a consequence, insignificant variations in the mechanical parameters [19] [20]. Experimental studies have been conducted on the behavior of FRP confined concrete under cyclic axial compression and the theoretical models for predicting such behavior in the open literature was developed [21] [22] [23] [24] [25].

Barney *et al.* (1978) [26] indicated that the large underestimation of beam deflections was primarily caused by neglecting important deformation components, such as shearing distortions, slip of the longitudinal reinforcement in beams and the effect of load reversals. Determination of shear distortions is necessary to accurately estimate the total coupling beam deflection particularly at displacement values exceeding yield. Shear distortions are likely affected by the extent of diagonal cracking in the beams. So the variation of shear stiffness as a function of displacement demand was measured throughout the tests.

2.2. Beam-Column Joints

Beam-column joints are critical regions of reinforced concrete frames designed for inelastic response to the seismic attack. Inadequately detailed joints especially exterior beam-column joints (Figure 2) may fail prematurely in a brittle manner due to high shear stresses. In earthquake-prone regions, the joints of ductile moment resisting (DMR) frames must be designed and detailed to allow large energy dissipation in adjacent plastic hinges without a significant loss of strength and ductility. Figure 2 and Figure 3 showed the beam-column and frame joints, respectively.

Christopher D. Stoakes, *et al.* (2011) [27] investigated eight full-scale beam-column connections with gusset plates to study the cyclic flexural behavior and performance of concentrically braced frame beam-column connections to evaluate the reserve lateral load-resisting capacity in concentrically braced frames. They evaluated the connection parameters effect such as angle thickness, bolt configuration, weld type and size, supplementary seat angle and end plate thickness. Results showed that the presence of each parameter contributes in shear strength increasing.

The cyclic behavior of three-story steel plate infilled walls (SPIW) that are composed of reinforced concrete boundary frames was investigated by In-Rak Choi, *et al.* (2011) [28]. The results compared with (RCIW) and a reinforced concrete frame (RCF). Results indicated that thin steel infill plates could be

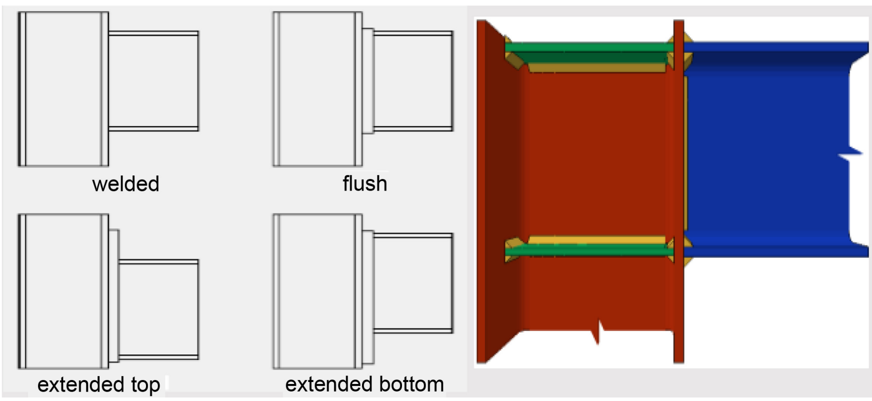


Figure 2. Beam-column connection types.

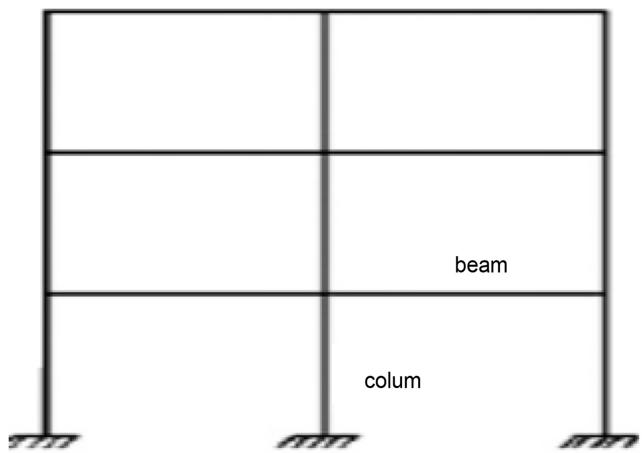


Figure 3. Frame type.

effectively used in the RCFs as well as the steel frames. The results obtained from (SPIW) specimens showed excellent strength, deformation capacity, and energy dissipation capacity in comparison with (RCIW) and (RCF). The test results showed that the displacement ductility and energy dissipation of the (SPIW) were higher than those of the RCIW by factors of 2.3 and 3.5 respectively.

The repair of two hybrid RC column-to-steel beams (RCS) connections severely damaged during earthquake type displacements is described by Gustavo J. Parra-Montesinos *et al.* (2001) [29]. The behavior of the repaired specimens is compared to that of the original specimens in terms of load-versus-displacement response, lateral stiffness, joint shear distortion, strains in the joint, transverse reinforcement and longitudinal column bars. They concluded that the growth of diagonal cracks and prevented FRP sheets controlled spalling of concrete in the corners of the joint.

Roberto Realfonzo *et al.* (2014) [30] investigated the seismic performance of RC beam-column joints strengthened with FRP systems. They concluded that the tests on repaired joints have confirmed the efficiency of the selected strengthening solutions and provided useful information on the adopted strengthening systems in terms of strength, ductility, and energy dissipation capacity of RC beam-column joints. The experimental investigations on two types of simple mechanical concrete beam-column connections subjected to reverse cyclic loading were carried out by R.Vidjeapriya1 and K. P. Jaya (2013) [31]. The load ratio, energy dissipation, ultimate load-carrying capacity, hysteretic behavior, equivalent viscous damping ratio, ductility factor, and strength degradation of both the precast and monolithic specimens were considered as main parameters. The results showed that ultimate load-carrying capacity of the monolithic specimen was superior to that of both the precast specimens.

J.G. Ruiz-Pinilla *et al.* (2014) [32] carried out the experimental tests on twenty full-scale internal beam-column joints to represent the seismic behavior of an RC frame structure. Results show that the strengthening techniques and the axial loads applied on columns can have a significant influence on the seismic behavior of the joints. Seyed S. Mahini *et al.* (2010) [33] examined the strength and ductility of FRP web-bonded RC beams to assess the behaviors of the retrofitted beam-column joints (RBCJ). The results show that the method used in their study is effective and capable for restoring or even upgrading the strength of the (RBCJ). In addition, using the basic principles of equilibrium and compatibility and an analytical model is presented the simplified analysis and design of this strengthening scheme.

An experimental program concerned with the response of RC walls under cyclic loading is presented by Kypros Pilakoutas *et al.* (1995) [34]. The discussion of the experimental results and comparisons between experimental and analytical work are presented. Cyclic behavior of RC cantilever walls was presented by Kypros Pilakoutas *et al.* (1995) [35]. The stiffness characteristics of RC members determine the level of loading likely to be imposed and guidance is given as to suitable load reduction factors. Limit states and deformational characteristics are investigated, and observations are discussed.

R. Realfonzo, *et al.* (2009) [36] investigated full-scale square columns reinforced by using both smooth and deformed steel rebars and subjected to a constant axial load and cyclic flexure load. In particular, two levels of the axial load were considered. Unidirectional carbon fiber reinforcement polymer (CFRP) or glass GFRP fiber layers used to confinement the specimens. They concluded that the total energy dissipated by the columns strengthened with FRP systems is much higher than that evaluated for the unstrengthened ones. Unconfined and confined members dissipate a comparable amount of energy until the collapse of the unconfined columns is achieved.

A full-scale RC structural wall subjected to cyclic loading designed according to European Seismic Code are studied experimentally by P. Riva *et al.* (2003) [37]. The results show that the collapse mechanism was governed by shear with the formation of a single large crack near the base section, almost parallel to the ground floor diaphragm leading to the tensile (necking) failure of the longitudinal wall reinforcement. Distributions of unit strain and curvature obtained with a dense array of non-contact coordinate-tracking targets at same wall are also presented [38] [39].

R. Giannini *et al.* (2008) [40] studied experimentally the cyclic response of an existing RC bridge pier to evaluate the failure mechanisms, collapse strength of the pier, calibrate of the numerical non-linear model and simulate the seismic behavior of the analyzed bridge. Test results show that the shear failure of the transverse beam at the first floor has been observed with a typical cracking pattern.

3. Analytical Studies

A review of existing analytical studies relevant to the seismic response of RC structures is presented in the following. Jin-Wook Hwang *et al.* (2013) [41] introduced a numerical slip model that can simulate the bond-slip phenomenon at the interface between a concrete slab and girder in composite beams subjected to cyclic loadings. They concluded through correlation studies between analytical results and experimental data that the inclusion of the bond-slip effect is important in evaluating the energy absorption capacity as well as the ultimate resisting capacity and the proposed model can be effectively used to predict the structural response under cyclic loading, and its application can be extended to a dynamic analysis of frame structures.

The first-ever study on the behavior and modeling of FRP-confined concrete under cyclic axial compression was presented by Yu-Lei Bai *et al.* (2013) [42]. A cyclic stress-strain model is then proposed and shown to provide close predictions of the test results. The proposed cyclic stress-strain model is formed by combining an existing monotonic stress-strain model for predicting the envelope curve with an existing cyclic stress-strain model for predicting the unloading and reloading paths.

The behavior of beams in which plastic hinges are formed under cyclic loading is examined by R. C. Fenwick *et al.* (1979) [43]. The results are reported of five beam tests, in which the shear stress level was varied. They reported that even relatively low shear stress levels have a significant influence on beam behavior. The degradation in shear under cyclic loading is accompanied by an appreciable growth in length of the beam. S. Tachibana, H. Masuya, and S. Nakamura (2010) [44] presented the performance-based design method for reinforced concrete beams under perpendicular impact load. Impact load characteristics such as the collision energy, the impact force duration, the energy absorbed by the beams, the beam response values and the impact behaviors are evaluated in experimental results. The validity of the proposed equation is confirmed by comparison with experimental results obtained by other researchers as well as numerical results obtained by FEM simulations.

G. Spadea and F. Bencardino (1997) [45] used the mechanical model to analyze and study the behavior of composite concrete sections reinforced with conventional steel bars and steel fibers and subjected to flexural cyclic loading beyond the yield point of steel bars. Their model is applied to study concrete sections reinforced with steel bars and steel fibers subjected to a flexural cycle with identical mechanical and geometrical specifications to the reinforced concrete sections. The numerical results are compared with experimental results that available in the literature.

Carmine Lima (2012) [46] presented an overview of the models currently available in the scientific literature for evaluating the shear capacity of exterior beam-to-column joints. A synoptic comparison among the analytical expressions of those models point out the key geometric and mechanical parameters which are supposed to control shear strength in exterior beam-to-column joints. A hysteretic moment-curvature relationship to simulate the behavior of reinforced concrete (RC) beam under cyclic loading and the nonlinear behavior of RC beams subjected to flexural cyclic loading is analyzed [47]. They concluded that the proposed model compared with experimental results and it can be effectively used to predict structural response under cyclic loading, and its application can be extended to the dynamic analysis of frame structure.

Y. Zhao, L. H. Xu, and B. Liu [48] presented an experimental study of the seismic behavior of reinforced concrete beam to concrete filled steel tube column connections with a ring beam. The displacements, the stresses, the failure patterns, the energy dissipation capacities of the tested specimens and the influence on the sectional dimension of the ring beam are considered as main parameters. The hysteretic curve of joint without ring beam shows a reverse S shape and a week energy dissipation capacity due to the slipping of the rebar which is caused by not dense concrete in the joint core area.

4. Evaluation of Structure Member Capacities in Some Codes of Practices

The shear strength of the beam V_n consists of concrete contribution V_c and shear reinforcement V_s contribution (Equation (1)) [49] [50].

$$V_n = V_c + V_s \tag{1}$$

where V_c is shear strength of concrete; V_s is shear trength of shear reinforcement.

Shear strength for inclined stirrup at an angle α with horizontal suggested as:

$$V_s = \frac{A_v f_{yv} (\sin\alpha + \cos\alpha) d}{s} \tag{2}$$

where A_v, f_{yv} are area of shear reinforcement in distance s and is the yield strength of shear reinforcement respectively.

When $\alpha = 90^\circ$ (vertical stirrups are used) the above equation reduces to

$$V_s = \frac{A_v f_{yv} d}{s} \tag{3}$$

The value of V_c is estimated using the ACI 318 code shear strength equation (ACI Committee 318-08) provided by concrete, as defined in the following equation:

$$V_c = \left(0.16\sqrt{f_c'} + 17 p_w \frac{V_u d}{M_u}\right) b_w d \tag{4}$$

where f_c' is concrete compressive strength, p_w is tension reinforcement ratio, d is beam effective depth, V_u is factored shear. The location of V_u in the member section is presented in **Figure 4** and **Figure 5**.

The empirical model developed by Yu-Chen Ou *et al.* (2014) [14] for corroded concrete specimens assume that V_c degrades with an increasing ductility of the specimen during the cyclic loading, and the degraded concrete shear strength (kV_c) as

$$1 \ge k = \frac{4 - \mu}{3} \ge 0 \tag{5}$$

where: μ is ductility.

The contribution of FRP (V_f) in shear strength of beam evaluated from [51]:

$$V_n = V_c + V_s + V_f$$

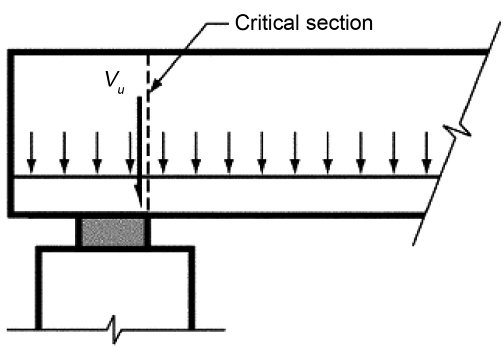


Figure 4. Location of critical section for shear in a member loaded near bottom [49].

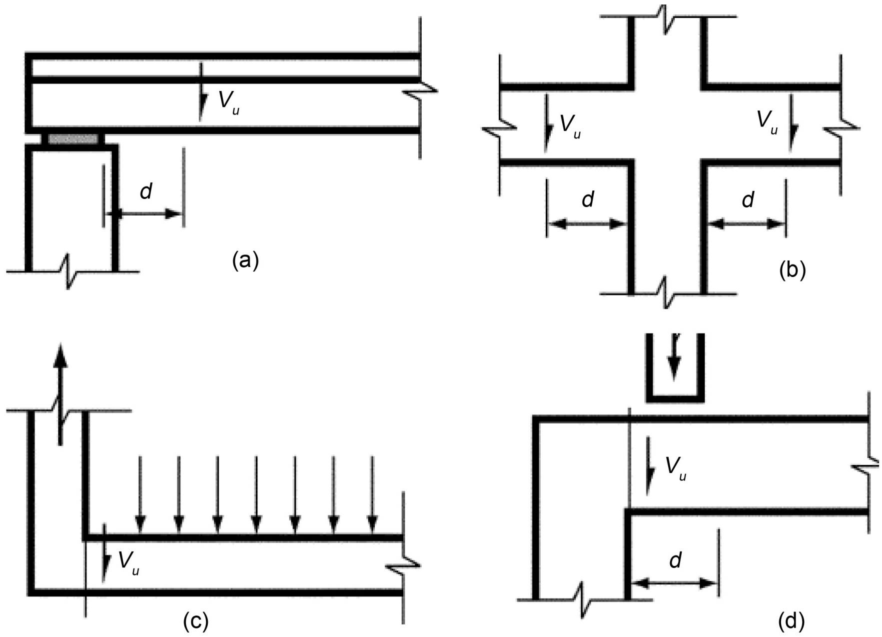


Figure 5. Typical support conditions for locating factored shear force V_u [49].

$$V_f = Kf_{fud}\left(\frac{A_f}{S_f}\right)\left(\sin\beta_f + \cos\beta_f\right)Z \tag{6}$$

where z = the lever arm length, taken as $d/1.15$. The term f_{fud} is the ultimate tensile strength of the FRP in MPa, which is reduced by an efficiency factor given as:

$$K = 1.68 - 0.67R \tag{7}$$

where K was determined through the regression of experimental results and is to be taken between 0.4 and 0.8.

The term R, is taken between 0.5 and 2, and is given by the following:

$$R = \left(\rho_f E_f\right)^{1/4}\left(\frac{f_{fud}}{E_f}\right)^{2/3}\left(\frac{1}{f'_c}\right)^{1/3} \tag{8}$$

The FRP reinforcement ratio is defined as follows (ACI 2008):

$$\rho_f = \left(\frac{A_f}{S_f b_w}\right) = \left(\frac{2t_f w_f}{S_f b_w}\right) \tag{9}$$

The interfacial bond stress level of the CFRP strips in Beam can be found using following equations [11]:

$$\tau = \frac{T}{w_f L_e} \tag{10}$$

where T is tension force, τ is interfacial bond stress, L_e is effective bond length

$$L_e = \frac{25350}{\left(E_f t_f\right)^{0.58}} \tag{11}$$

5. Conclusion and Recommendation for Future Studies

This paper reviewed the existing research works on reinforced concrete (RC) elements such as beams, columns and walls strengthened by CFRP, GFRP and steel reinforcement or steel plate and settled the baseline for future researches. In spite of the large number of experimental and theoretical studies on the monotonic stress-strain behavior of reinforced concrete elements under cyclic load, few theoretical and experimental studies have been conducted on the behavior of precast and pre-stressed RC beams under cyclic load while few theoretical models for predicting such behavior in the open literature were developed; furthermore, no literature about effect of cyclic load on RC beams or slabs with openings.

Future researches need more studies in RC structure especially in precast and pre-stressed reinforced concrete beams with openings, to improve the understanding of RC beams under seismic, dynamic or cyclic load when strengthened with FRP or steel plate to study the parameters such as end of anchorage, failure mechanism, FRP orientation, number of FRP layer, spacing, strength scheme and shear capacity. Finding a relation between several parameters such as shear span, effective span, loading type, beam dimensions and strengthening types also are important.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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