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Review Article

Shear Strengthening and Rehabilitation of Normal Reinforced Concrete Beams: A Review

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Abstract

The structural integrity of reinforced concrete (RC) structures diminishes over time due to ageing, unexpected loads such as earthquakes, and corrosion-induced deterioration, necessitating rehabilitation or replacement. Insufficient shear capacity and lack of ductility in normal RC beams lead to extensive damage during earthquakes. Addressing shear deficiencies is critical as they are more hazardous and can lead to sudden failure. Shear strengthening of RC beams enhances their load-carrying capacity and prevents brittle shear failures. This paper reviews several methods of strengthening beams in shear, focusing on the Fiber Reinforced Polymers (FRP) method for strengthening beams in shear as ACI 440.2R fully covers the design procedure. To enhance the shear strength of a concrete beam using FRP, the shear force contribution by the composite should be estimated, and a suitable system should be selected, such as two-sided, three-sided wraps or a fully wrap system of the application. Then, the spacing between the FRP strips should be found. The beam would be properly strengthened for shear using FRP sheets.

1. Introduction

Over time, numerous reinforced concrete structures worldwide lose their strength as they approach the end of their lifetime. Therefore, they need rehabilitation or complete replacement. Other reasons leading to the requirement for strength enhancement are unexpected loads, such as earthquake and dynamic loads, and corrosion-induced deterioration [1]. Strengthening existing reinforced concrete (RC) beams is required for various reasons such as increased loading after construction, capacity loss because of material deterioration or errors in early stages of design and construction. The general strengthening practice recommends avoiding brittle shear failure by strengthening both the flexural and shear. Particular reasons for deficiencies in shear areas may be due to some factors vis. Low shear reinforcement in shear resisting area, deterioration of steel area due to corrosion, increased applied load, and both design and/or construction defects [2].

The Hyogoken– Nanbu Earthquake in 1995 resulted in tremendous damage to most of the concrete structures in Japan. Because of the earthquake, numerous reinforced concrete rigid frames and some piers used for elevated highways were rigorously damaged and failed. Lack of ductility and insufficient shear capacity of these structures' piers and main beams were believed to be the main reasons behind their failure [3]. This can be interpreted as those elevated highways constructed in Japan that were built based on the design specifications issued before 1980, where those codes did not fully tackle the ductility-related problems. Therefore, similar structures need special care at the design stage as they are vulnerable to natural disasters like earthquakes [4].

It is crucial to know the structural deficiencies in Reinforced Concrete (RC) members, which can be mainly categorized into two main parts: flexural or shear, even though deficiencies categorized under shear are fundamentally more hazardous because they occur suddenly and with little possibility of internal force distribution. Therefore, shear strengthening of beams with strength deficiency is essential despite the cost needed, even though funds dedicated to infrastructure rebuilding and rehabilitating are particularly curbed [5].

According to V. Garg [6], shear failure in beams with or without shear reinforcement has three phases, as shown in Figure 1. The first phase starts from the appliance of the load to the appearance of the first flexural crack, called flexural crack. The second phase is the appearance of the flexural cracks in the middle of the beam and the propagation of the flexural cracks. The third phase is the appearance of diagonal cracks from the supports to the point loads applied on the beam, which start to fail and become dangerous due to severe cracking and deflection. The size of the diagonal cracks increases dramatically, leading to ultimate collapse of the beam as it cannot carry any extra load if it remains unreinforced [7]. Meanwhile, in the beams with shear reinforcements, the beam will carry more load until the flexural reinforcement or shear reinforcement is yielded, and the beam collapses. These phases are well accepted by other scholars such as W. Abdullah [8].

1.1. Mechanism of Failure

When the transverse steel reinforcements in an existing concrete beam cannot provide sufficient shear capacity, shear strengthening is needed regardless of the techniques that will be used on the sides of the beam. The mechanism of failure in RC beams has several steps [9]. Initially, when the loading is applied, the first stage of shear failure of the beam member is necessitated when an inclined crack forms in the shear span. After that, the steel stirrups, if they exist, will bridge the gap caused by the crack and transfer the stress back to the concrete. Therefore, other inclined cracks will form. The cracking path is best noted when a member is strengthened externally with FRP strips or metal straps because the cracks will be easily seen on the concrete beam surface between the strips [9].

The ultimate failure of a beam subjected to shear force is primarily due to the crushing or breaking of the concrete, and thus, the ultimate strength is closely related to the concrete's strength. According to Z. Guo [10], different shear span ratios of $\lambda = a/h$ where a is the shear span between the point load to the support and h is the height of the beam, result in different failure patterns, which means the beam's strength is influenced by either the compressive or tensile strength of the concrete as shown in Figure 2.

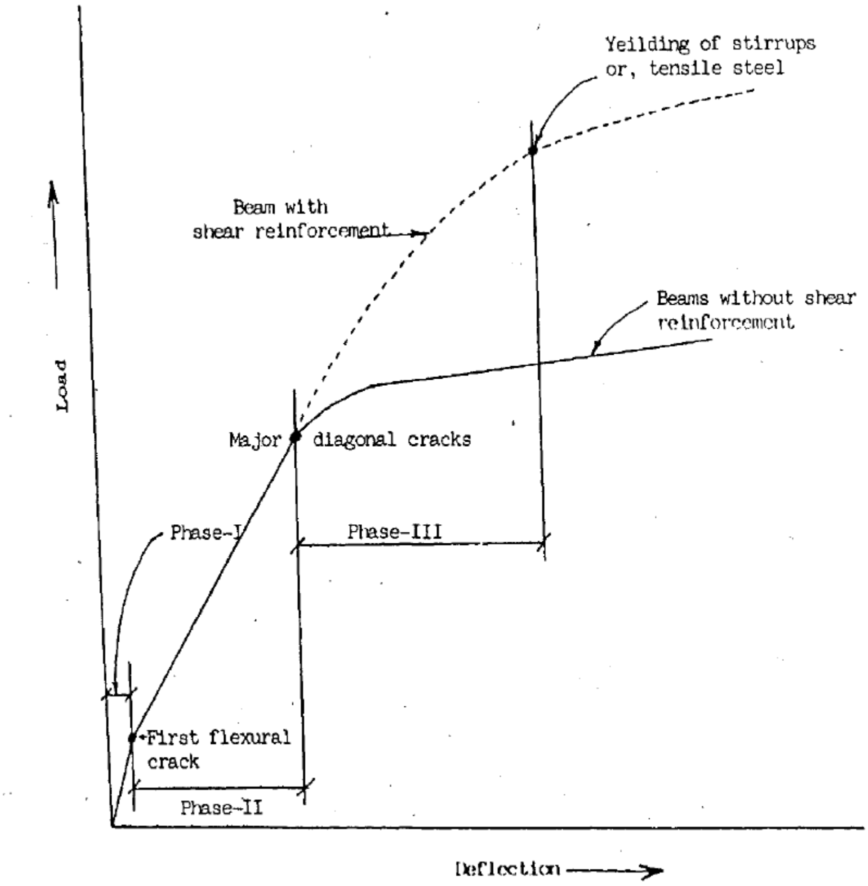


Figure 1. Phases of shear failure in RC beams [6]

For beams with smaller shear span ratios (λ < 1), failure occurs through inclined compression, which depends on the concrete's compressive strength, leading to an ultimate strength that increases proportionally with the concrete's compressive strength. Beams with larger shear span ratios (λ > 3) fail through inclined tension, relying on the concrete's tensile strength, resulting in a slower increase in ultimate strength with the strength of the concrete. Beams with medium shear span ratios (λ = 1-3) fail through shear-compression, influenced by both the compressive strength of the concrete near the top of the beam and aggregate interaction along the critical inclined crack. Thus, the rate of increase in ultimate strength for these beams falls between the rates for the other two types.

2. Methods of Strengthening for Shear in Beam

Several methods of strengthening for beams that failed in shear can be found in the literature, most commonly:

2.1. Enlargement of the Section

The method provides a new case or a layer of reinforced concrete beam to an existing beam that contributes to carrying both flexural and shear load [11].

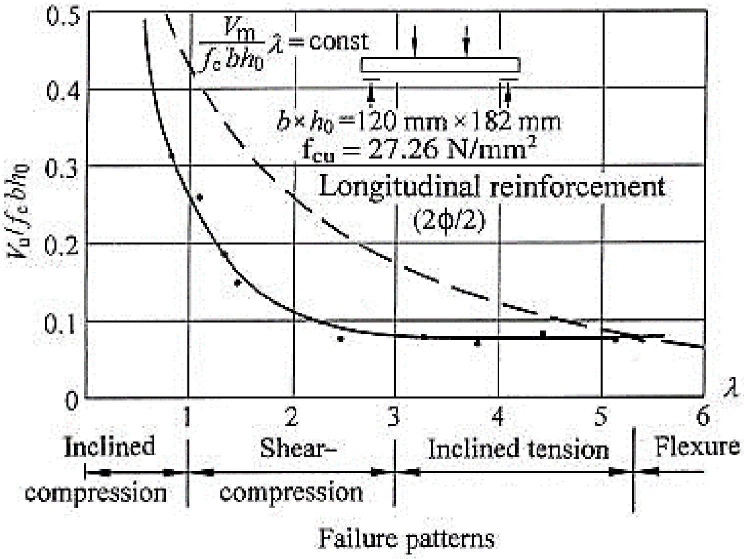


Figure 2. Beam Failure Mechanisms [10]

According to V. Garg [6], it has three different forms: casting (see Figure 3), jacketing (see Figure 4) and building up (see Figure 5). If the entire section is cased with reinforced concrete, it is called casting [6].

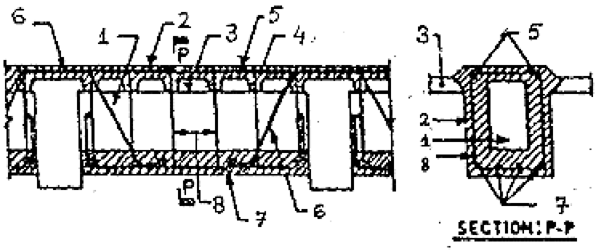


Figure 3. Casting method in section enlargement [6]

In jacketing, only three sides of the beam will be enveloped by reinforced concrete, as shown in Figure 4.

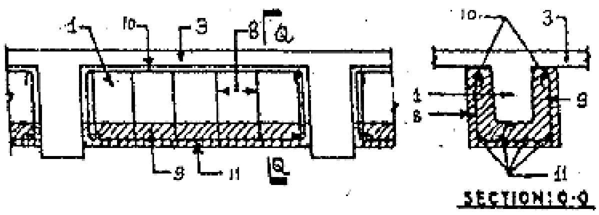


Figure 4. Jacketing method in section enlargement [6]

Building up can be done for one of the sides of the beam, as shown in Figure 5. Generally, the thickness of the concrete layer varies between 50 mm to 100 mm in section enlargement, depending on the strength requirement.

Wang et al. [11] reported the results of their tests on reinforced concrete (RC) beams strengthened in shear using external reinforcement with either RC or epoxy resin mortar. Their test specimens measured 2000 mm in length with a cross-section of 150 mm×200 mm, which was increased to 250 mm×300 mm after section enlargement. The shear span to beam depth ratio (λ) was 2.35. All specimens had identical geometries but varied in stirrup configurations as the primary variable tested. During the first testing phase, no shear reinforcement was applied, whereas in the second phase, external RC or epoxy resin mortar was used to prevent the shear failure. The experiments aimed to examine the effects of preexisting damage, stirrup configurations, and different methods on the behavior and failure modes of the strengthened beams. A control group of unstrengthened beams failed in shear, while all strengthened beams demonstrated a significant increase in ultimate load capacity when failing in shear. They found that section enlargement with RC enhanced concrete beams' ductility and ultimate shear strength by at least 150%. The method of section enlargement with RC was determined to be effective in improving shear capacity.

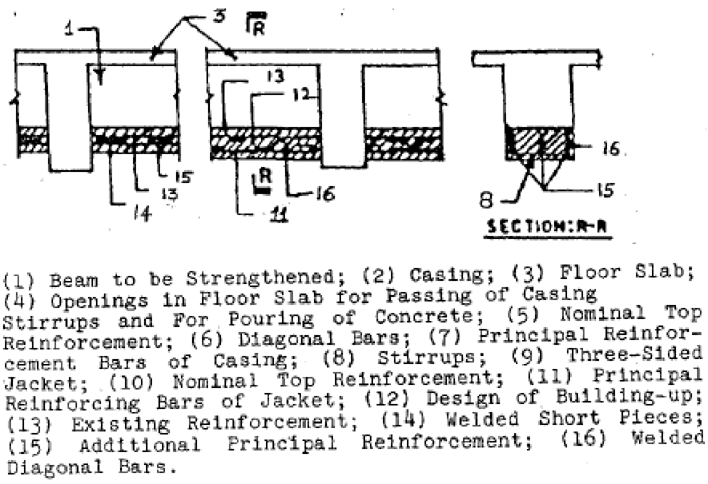


Figure 5. Building up method in section enlargement [6]

2.2. Stressing Externally

Post-tensioned metal bars can exert an extra compressive force on the beams when the tensile stress develops inside the beam before cracking[12]. S. H Lee et al. [12] examined a post-tensioning method using externally unbonded steel rods to strengthen pre-damaged reinforced concrete beams flexural. In their study, nine supported beams underwent three-point bending tests, including three reference and six post-tensioned beams, as shown in Figure 6. The design parameters considered were the number of tension reinforcements (3-D19, 4-D19, and 2-D22 + 2-D25, with "D" indicating the nominal diameter of the rebar) and the diameters of the external rod (φ22 mm and φ28 mm). A V-shaped profile with a deviator at the bottom of the mid-span was applied to the pre-damaged beams, and a post-tensioning force was added to counteract the low loading resistance and deflection present in the pre-loading state. The post-tensioning force, achieved by tightening nuts at the anchorage, corresponded to a strain of 2000 με in the external rods. The post-tensioning system increased the load-carrying capacity and flexural stiffness by approximately 40–112% and 28–73%, respectively, compared to the control beams. However, in post-tensioned beams with larger steel reinforcements and external steel rods, the external rods did not yield. The larger diameter external rod more effectively increased the flexural strength.

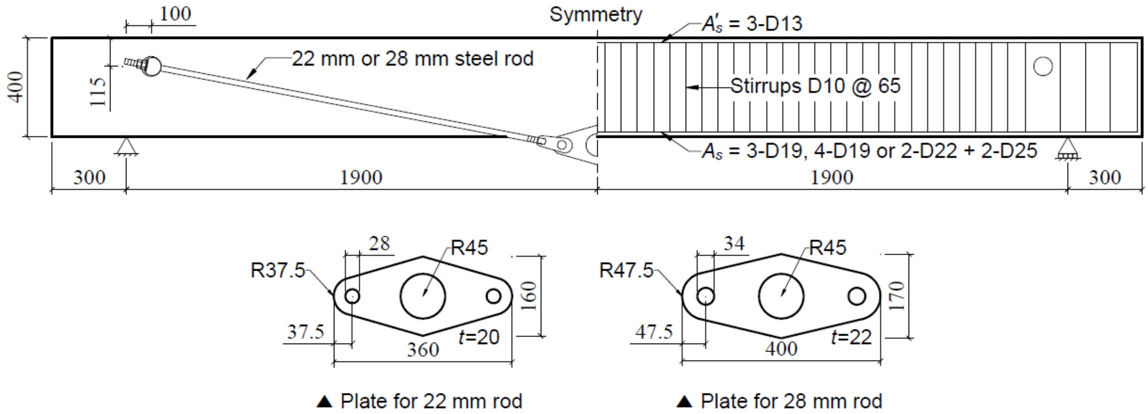


Figure 6. Strengthening using post-tensioned bars [12]

2.3. Externally Prestressing

In the process of strengthening beams and roof girders, sometimes, external plates are anchored to the beam, and external tendons are post-tensioned to the beam going through it. If the tendons are fixed suitably, they can be used to balance the applied forces on the beam or at least cancel out the beam's self-weight with a portion of applied actions [13]. The application of this method is shown in Figure 7.

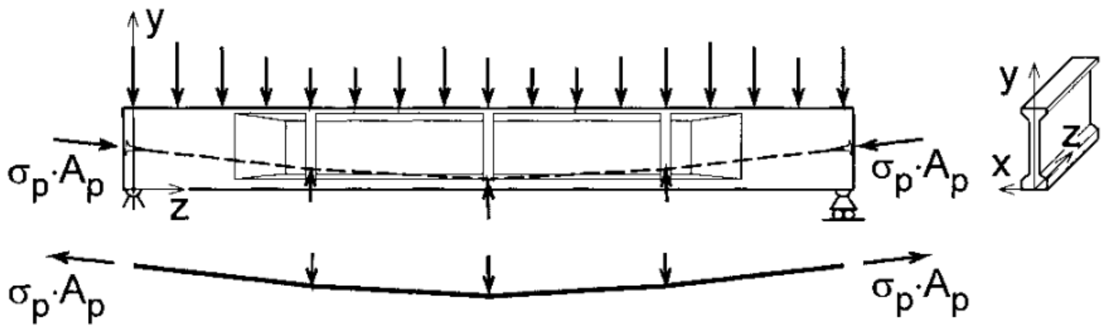


Figure 7. External prestressing [13]

2.4. Gluing Steel Plates

It can be used to enhance the stiffness and strength of the defected beams. It can be used when the concrete is unsuitable for drilling, which is more effective despite being expensive and time-consuming. In this glueing method, epoxy is used to connect the steel plate to the surface of the beam. The thickness of the glue or adhesive layer is recommended to be between 1 mm and 3 mm after cleaning the surface of the concrete and embracing the steel plate to the face of the beam by B. Babu [14]. They tested two control beams and ten beams with steel plates bonded to their webs. They observed that the shear strength of defected beams increases with plate thickness and depth. A maximum 84% increase in ultimate shear strength was observed in beams with steel plates over the control beams. The only problem with using this method is the insurance of the bond between the plate and the beam. The application of this method is shown in Figure 8.

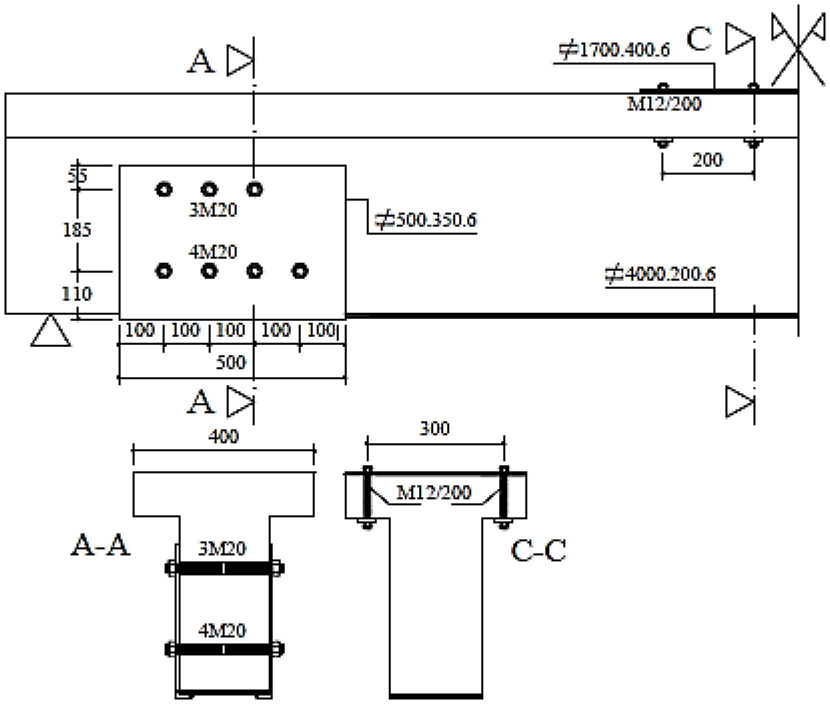


Figure 8. Steel plate with epoxy [15]

Through a series of tests, Ozbek, Bocek, and Aycak [13] investigated an end connection detail for externally plated reinforced concrete (RC) beams. They tested four full-scale RC beams, including one control beam and three beams were strengthened against flexure. They had T-beams with a width of 200 mm, an overall height of 500 mm, and a total length of 4500 mm. The flange measured 100 mm in thickness and 400 mm in width. All specimens, including the control beam, were reinforced with 3Ø14 tension reinforcing bars and 2Ø10 and 4Ø8 compression reinforcing bars. The test results of these plated RC beams strengthened with this connection detail, shown in Figure 8, were compared with those of a monolithic RC beam with identical dimensions. The study examined the influence of using a compression plate in addition to the tension plate and the external plate's epoxy bonding on the plated beams' behaviour. The yielding load values of the specimens were also compared to the analytical values calculated from equivalent rectangular stress block analysis. They concluded that the external plates with the end connection detail presented increased the yielding loads of the plated beams by 150-170% and the ultimate loads by 130-160%. Additionally, the strengthening plates resulted in a limited decrease in ductility while increasing the modulus of toughness values.

2.5. Strengthening Using Steel Fibrous Concrete

Steel fibrous concrete is an excellent alternative to other methods of strengthening beams in shear because steel fibrous concrete offers ductility. It will enhance the strengthened section's shear strength, stiffness, and energy absorption properties [16]. The repair consists of repairing and recasting the beam's damaged portions using fibrous steel concrete, as shown in Figure 9.

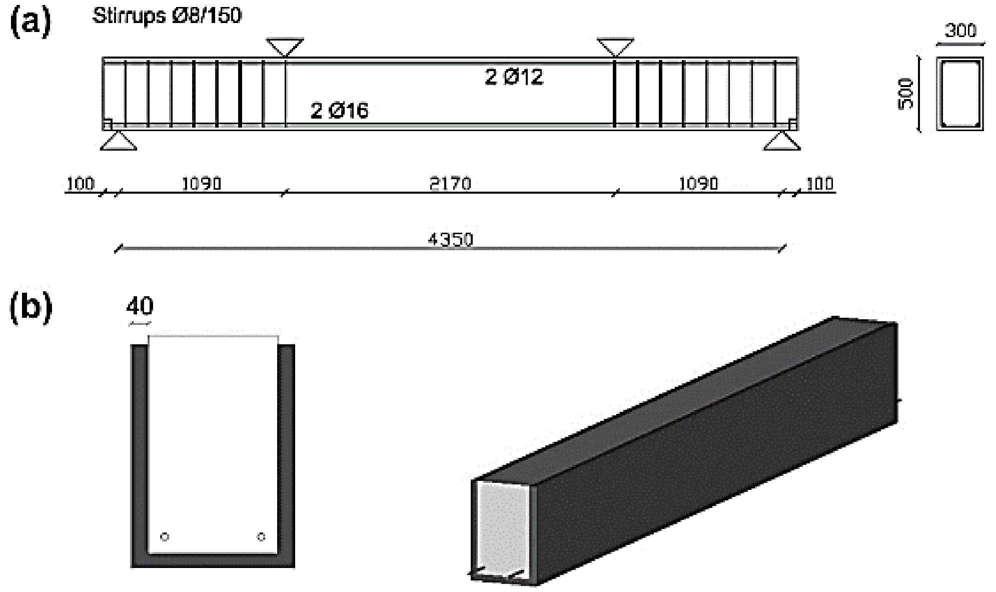


Figure 9. Using fibre-reinforced concrete for strengthening [16]

2.6. Strengthening Using Ferrocement

It is another technique that is used to strengthen the beams that fail in shear. Some researchers, such as Alrifaie et al. [17], worked on using this method, as shown in Figure 10. They proved that the original ultimate load/ultimate load after rehabilitation might reach 100%, which means it will regain its original strength using this method of strengthening [17].

Figure 10. Strengthening using Ferrocement [17]

2.7. Nanomaterial Injection

It is a novel method, shown in Figure 11, that has been used to strengthen the beams with shear deficiency. It is proven that using nanomaterials to inject the beams can restore 80% of the carrying capacity to the beams that have failed in shear [17].

Beam during repairing using the injection technique.

Figure 11. Strengthening using nanomaterial injection [17]

2.8. Strengthening Using Self-Compacting Concrete

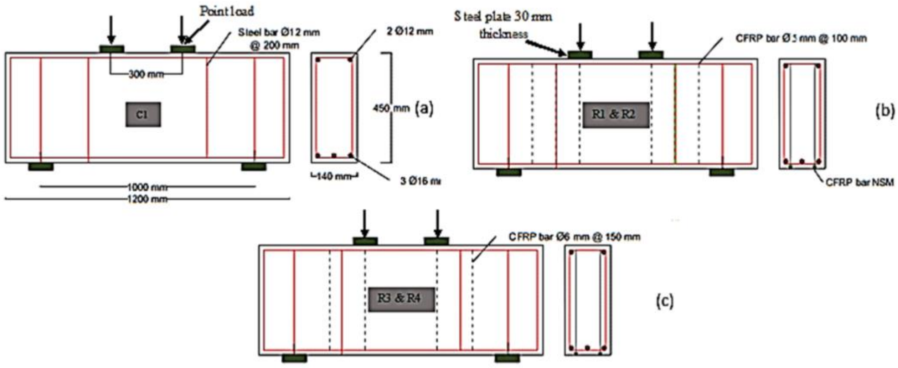
It involves recasting the self-compacting concrete (SCC) to the damaged beams. Chlaioris and Pourzitidis [18] worked on using this method, as shown in Figure 12. They examined SCC jacketing and concluded that it is an easy method to apply; however, its effectiveness is not satisfactory for damaged RC beams even though the load-carrying capacity of the jacketed beams was fully restored or enhanced compared to the initially examined beams. A significant increase in the loading bearing capacity that varied from 35% to 200% for the retrofitted beams compared to the corresponding initial beams was observed [18]. Based on observation, the precision of work with this method is not relatively reliable as it covers a wide range of strength improvement from 35% to 200%.

(a) (b) (c) (d)

Figure 12. Strengthening using self-compacted concrete [18]

2.9. Near Surface Mounted (NSM)

NSM is a desirable and novel method for rehabilitating and strengthening damaged reinforced concrete structures. Generally, the NSM method contains cutting grooves along the concrete surface or concrete cover of the structural member and then installing carbon fibre-reinforced polymer (CFRP) bars into these grooves, as shown in Figure 13. These CFRP bars will be covered by epoxy resin. Many researchers worked in the field of strengthening of the beams failed in shear using this technique [1] [2].



(a) Control beam C1 (b) Beam specimens R1 and R2 with CFRP anchor bars at 100mm c/c (c) Beam specimens R3 and R4 with CFRP anchor bars at 150 mm c/c.

Figure 13. FRP- NSM strengthening method [19]

2.10. TRM Method

Recently, it has been proposed that textile-reinforced mortar (TRM) be used in structural retrofitting and strengthening as a new composite material and replacement for available materials. TRM or fabric-reinforced-cementitious-matrix (FRCM), as some references refer to it, combines textiles, which is a form of advanced fibres (with configuration of open-mesh) with inorganic matrices, such as cement-based mortars. The advantages of using TRM are that it is a comparatively low-cost material, friendly to use, easy for workers who use it manually, and well-matched with concrete or masonry units. Moreover, it can be used at very low temperatures as well as on wet surfaces [20]. In the literature, there is another name for the same material: FRCM. More research is needed to investigate the bond between TRM or FRCM and concrete substrates. Several researchers have worked on this technique and investigated its efficiency [20].

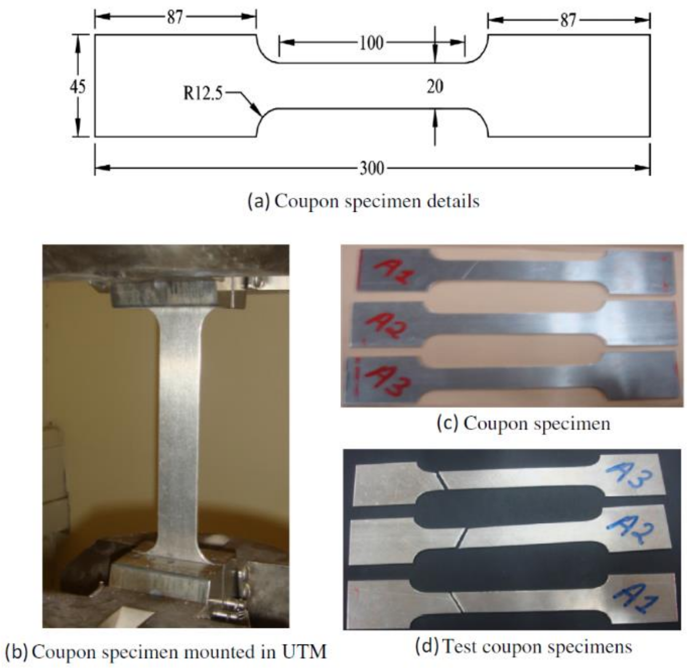


Figure 14. High-strength aluminium alloys or (AA) [21]

2.11. Externally Bonded Aluminum Alloy Plates

Developed recently, high-strength aluminium alloys (AA), as shown in Figure 14, have suitable characteristics that make them stand out as externally bonded strengthening materials. In the literature, Abdalla [21] worked on the efficiency of this method. In their study, they proved that using this method in strengthening beams that failed in shear can fully restore the member's load-carrying capacity.

2.12. Post-Tensioned Metal Strap

Abdullah, W. [8] used post-tensioned metal straps (PTMS) to strengthen reinforced concrete building members. They studied the effectiveness of PTMS fully wrapped around medium-scale steel-reinforced concrete (RC) beams to enhance their shear strength. They cast four normal RC beams without transverse reinforcement, with dimensions of 160 mm × 240 mm × 1050 mm (width, depth, and length, respectively). PTMS was fully wrapped around the beams at different locations using varying numbers of strips for strengthening, as shown in Figure 15. The study found that PTMS can effectively change the failure mode of the beams from brittle shear failure to ductile bending failure, as shown in Figure 15. Additionally, the load-carrying capacity of the beams increased by 143%, 170%, and 182% with the use of two, four, and six PTMS strips, respectively. Moreover, the deflection capacity increased by 643%, 557%, and 653% with two, four, and six straps of PTMS, respectively. Lastly, using PTMS on the beams reduced the number of cracks and localized their appearance to the centre of the beams.

Figure 15. Changing behavior of the beam failed in shear to bending [8]

2.13. Strengthening Using FRP

Generally, despite their type, FRP sheets possess high tensile strength and corrosion resistance with a very thin layer, are lightweight, and can be used to increase shear capacity significantly with efficiency [22], even though they have some drawbacks of being brittle and expensive [2].

The effectiveness of this method varies based on tested variables in the literature, such as the existence of steel shear reinforcement in the beam, the ratio of shear span-to-effective depth, and the CFRP amount that has been used and their distribution [23]. The tested beams in the Khalifa and Nanni program [2] noted an increase in shear strength of 40 to 138% in beams strengthened with FRP, as shown in Figure 16. Many other researchers used FRP in strengthening the beams [5, 22, 23-32, 33].

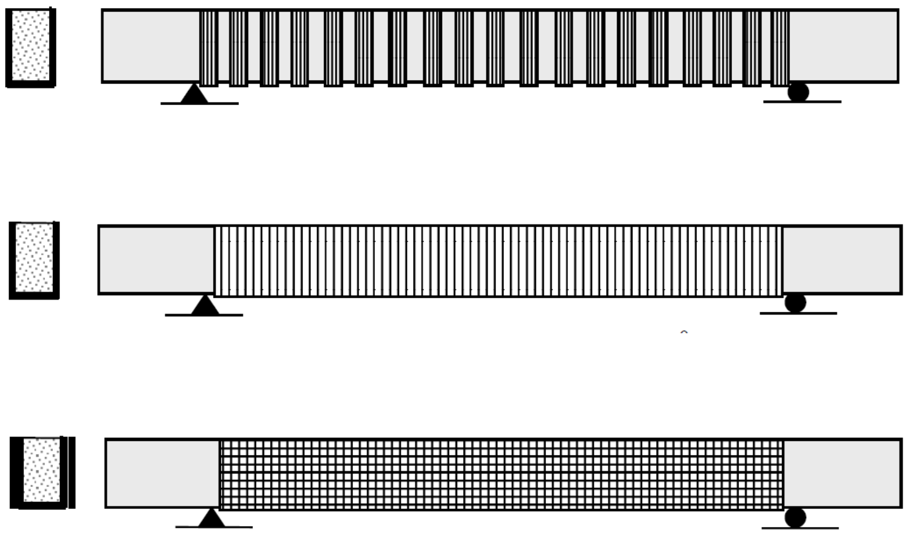


Figure 16. Beams strengthened with FRP sheets [2]

Bukhari et al. [22] tested seven two-span concrete continuous beams with rectangular cross-sections, as shown in Figure 17. The control beam was not strengthened, while the remaining six were strengthened with different arrangements of CFRP sheets. The experimental results indicated that the CFRP sheets significantly increased the shear strength of the beams and that orienting the FRP at 45 degrees to the axis of the beam was beneficial. The shear strength of FRP-strengthened beams is typically calculated by adding the individual components of shear resistance from the concrete, steel stirrups, and FRP.

3. Factors influencing the shear contribution generally and of FRP in specific

3.1. Effect of Stiffness

The main problem associated with using FRP as a method of strengthening is debonding; its increase is directly proportional to the increase in stiffness. Triantafillou [23] suggested an equation to take the FRP stiffness by ρfEf (the product of area fraction and Young's modulus of the FRP) and claimed and argued the dependency of the effective FRP failure strain (εfe) on stiffness parameter.

3.2. Effect of Concrete Strength

The compressive strength of the concrete can directly and indirectly affect debonding. It indirectly influences debonding as it is governed by concrete surface properties, mainly its surface tensile strength and interfacial fracture. Khalifa et al. and Triantafillou and Antonopoulos [34], [35] took εfe as proportional to f 2/3c. They also proposed empirical equations that can be used to calculate the effective failure strain from (Ef ρf /fc 2/3). Later on, these equations were adopted in the FIB design guidelines.

3.3. Effect of Strengthening Configuration

The FRP's Failure mode can be affected by strengthening configuration [36]. In some configuration types, debonding might occur, such as in U-jacketing and both side bonding, knowing that the loading resistance of side-bonded FRP is generally less than other configurations as no anchorage is at either end of the FRP. However, when full wrapping is used, the failure mode changes to FRP rupture with a higher effective failure strain than complete debonding. For this reason, full wrapping is recommended when FRP is being used for strengthening, as it is quite effective. The least favourable method is side bonding, and a moderate method would be U-jacketing. Moreover, it is desirable to use anchorage to the free edges of FRP whenever U-jacketing and side bonding are used. Experiments must check this anchorage's effectiveness.

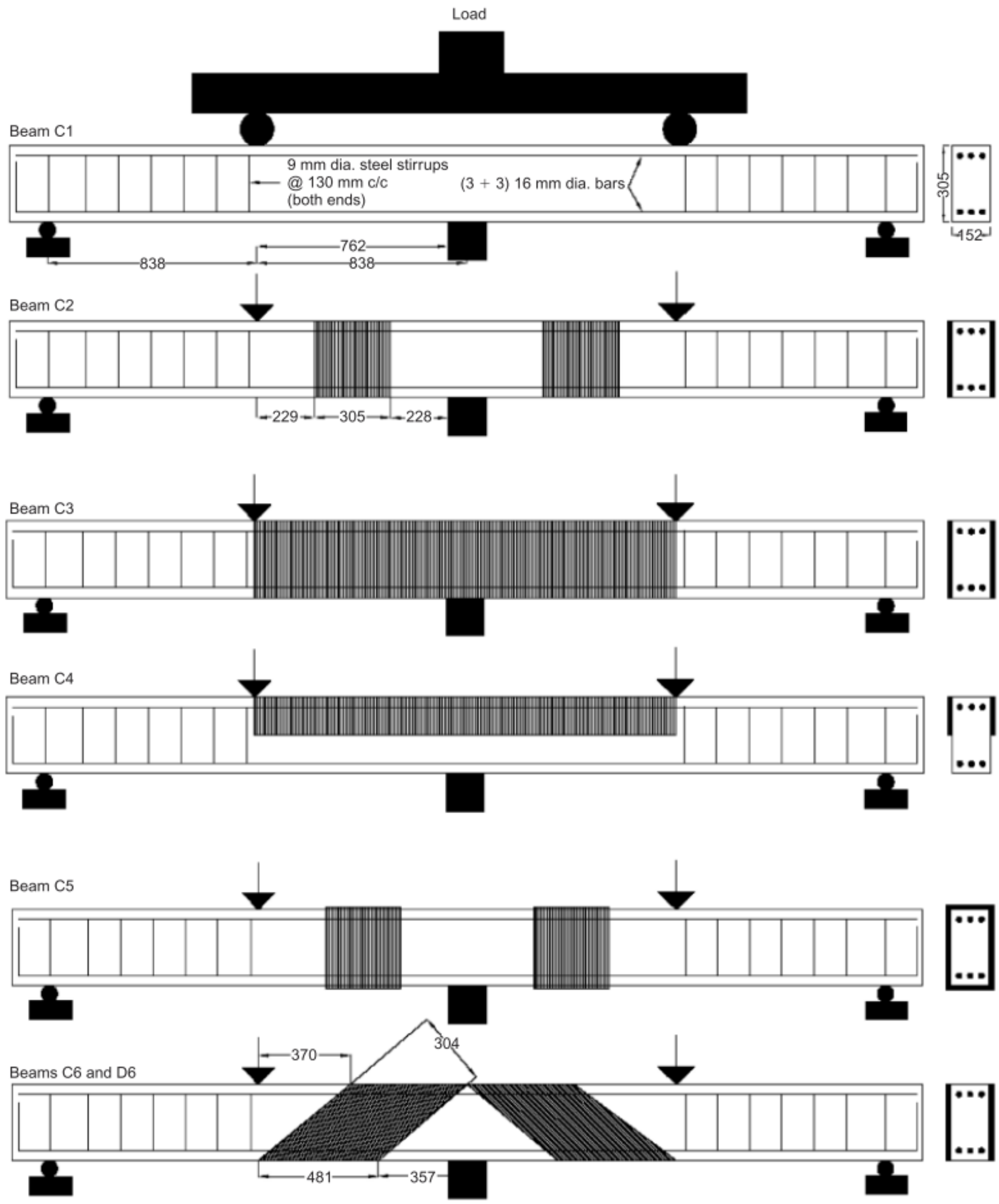


Figure 17. Detail of the beams tested by Bukhari et al. [22]

3.4. Effect of Steel Shear Reinforcement Ratio

Regarding the shear strengthening of beams, it is proven in the literature that the ratio of steel shear reinforcement has tremendous effects, especially for beams that are strengthened and failed by the complete debonding of side-bonded FRP strips [36]. Based on experimental results, an increase in the stiffness ratio between bonded FRP and steel shear reinforcements decreases the effectiveness of shear strengthening. This relationship is given by ρs,f = EsAsv / EfAf.

Physically, the cracking pattern changes with an increase in steel stirrups in beams. For instance, only a single crack will form in the whole shear span when there is no shear reinforcement in the beam. Additionally, the stress moves back into the concrete beam, causing more cracks to form and more steel reinforcements in the beam. Finally, debonding will occur as the FRP sheet faces many openings from the cracks.

3.5. Effect of Member Size

It is proven from the literature that the beam size does affect bonding when U-jacketing and side bonding are used for strengthening the beams [36]. It is also proven that for the configuration above methods, with an increase in member size, the effectiveness of the strengthening will decrease. However, the failure load ratio between strengthened and controlled beams is nearly the same when full wrapping is used for strengthening.

3.6. Effect of Shear Span-to-Depth Ratio

Different span-to-depth ratios affect the beam's failure mode, as described at the beginning of this report. In the literature, different ranges of shear pan to depth (1 to 3) have been tested and strengthened against shear failure using FRP bonding. The effectiveness of this method was confirmed for the whole covered range. However, more studies are needed to understand the behaviour of FRP bonding with other different ratios [36].

4. Design of Shear-Strengthened Concrete Beams with FRP Based on ACI 440.2R [36]

When FRP bonding is used with a concrete beam, finding the section's strength can be done by presuming that the FRP can behave as steel shear reinforcements, and its contribution (Vf) is added to those from the concrete and longitudinal steel reinforcements (Vc) and the transverse steel reinforcements or bent-up bars (Vs). The total shear capacity (V) is then given by equations 1 and 2:

$$\emptyset V_n \geq V_u \tag{1}$$

$$\emptyset V_n = \emptyset(V_c + V_s + \psi_f V_f) \tag{2}$$

Knowing that:

ψ_f=0.95 Completely wrapped members

$\psi_f = 0.85$ Three-side and two-opposite- sides schemes

To find Vf, first, it is required to have an effective FRP strain at failure (εfe). Full wrapping, U-jacketing and side bonding are taken care of in equation 3 as it is provided in the design code of ACI 440.2R:

$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_{fv}}{s_f} \quad (3)$$

Where $A_{fv} = 2nt_f w_f$

dfv is the effective length of the FRP, equal to the FRP length minus the length from the bottom of the beam to the centroid of the tensile steel reinforcements. α is the principal fibre orientation for an FRP sheet or the inclination of an FRP strip (with fibres running along the strip). Also, θ is the inclination of the shear crack, which is 45 degrees. If FRP strips are used, the centre-to-centre spacing is given by sf, and Afv is equal to 2tfwf, where tf and wf are the strip thickness and width, respectively. For an FRP sheet, (Af /sf) is replaced by 2tf . Figure 18 shows the details of the beams.

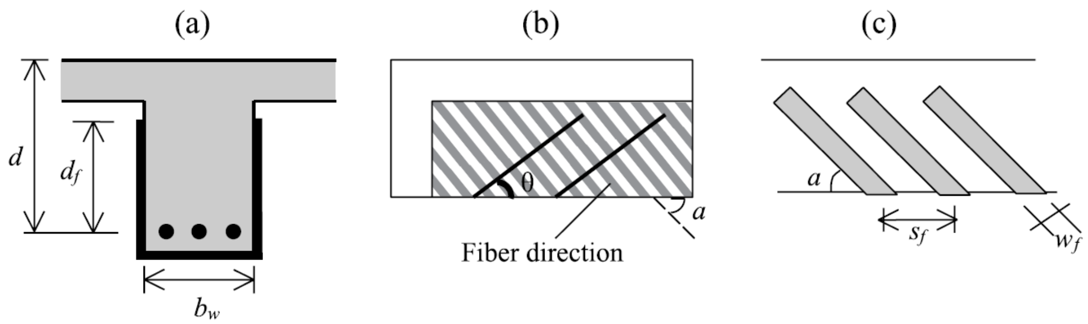


Figure 18. Different FRP applications on beams [36]

To find the mean effective failure strain (εfe), the following cases are used: For full wrapping or FRP that is properly anchored, failure occurs by FRP rupture, and the effective failure strain is given by:

$$\varepsilon fe \ = \ min(0.75\varepsilon fu, 0.004)$$

εfu is the rupture strain of the FRP. The effective failure strain is limited to 0.004 to ensure that aggregate interlock is maintained when ultimate failure occurs.

For U-jacketing or side bonding, εfe = min (κνεfu, 0.75εfu, 0.004), where $\kappa\nu$ is presented from eq(4) to (7)

$$\kappa_v = \frac{k_1 k_2 k L_e}{11900\ k\epsilon_{fu}} \quad (4)$$

With

$$L_e = \frac{23300}{(t_f E_f)^{0.58}} \quad (5)$$

$$k_1 = (\frac{f_c}{27})^{2/3} \quad (6)$$

$$k_2 = \begin{cases} \dfrac{d_f - L_e}{d_f} \ for\ U - Jacketing \\ \dfrac{d_f - 2L_e}{d_f} \ for\ Side\ Bonding \end{cases} \quad (7)$$

The design equations proposed above do not take the effects into proper consideration of span depth ratio, member size and steel reinforcement ratio on the FRP failure strain εfe. With additional experimental results available in the future and better models developed to quantify the various effects, these equations will be refined. Note, to ensure the validity of this assumption, the ultimate shear capacity (V) should be limited to vubwd, with vu = 0.8_fcu but not exceeding 5 N/mm2.

It is usual to assume the angle of failure as 45 degrees to the longitudinal axis and provide vertical steel stirrups in beams to intersect with the cracks as they form. Specifying the maximum spacing of the FRP effective depth to the steel stirrups should be considered. When designed, the spacing of the FRP strips should be as small as possible because it is necessary to guarantee the crack intersects with at least one FRP strip, which provides sufficient at the intersection location. For example, if at a place near its free edge, side bonded FRP is being used, it will intersect with the crack, and this might cause a complete debonding to occur; therefore, its effectiveness is close to none. It is preferred to have the intersection of the crack with the FRP at a location as far away as possible from the edges. It is recommended in the literature to have an intersection between at least two FRP strips and a crack. In the ACI 440.2 R, the maximum strip spacing is then given by equation 8:

$$s_f \leq s_{f,max} = \frac{d_f(\sin\alpha + \cos\alpha)}{2} = \frac{d_f}{2} \; if \; \alpha = 90° \tag{8}$$

Where d_f is the effective depth of the FRP strip,

5. Design Procedure

Step 1: Determine the critical section and compute Vu's maximum shear force for the factored loads. The critical section is at a distance, d, from the support provided that the loads introduce compression into the end region of the member, and there are no concentrated loads between the support and distance, d.

Step 2: Compute Vc and check using equation 9 whether

$$\frac{V_u}{\emptyset} - V_c \leq 8\sqrt{f'_c}b_w d \tag{9}$$

If this condition is not satisfied, the section needs enlargement since composites are used to enhance the existing structure. The condition might control the design if heavy shear reinforcement is provided in the original design.

Step 3: Compute the shear contribution of existing steel reinforcement using equation (10):

$$V_{cs} = \frac{A_v f_y d}{s}(\sin\beta + \cos\beta) \tag{10}$$

For vertical stirrups, (sin β +cos β) =1

Step 4: Estimate the shear to be carried by composite using Equation 11, Vf :

$$V_f = \frac{1}{\psi_f}\left[\frac{V_u}{\phi} - V_c - V_s\right] \tag{11}$$

ψf is 0.85 and 0.95 for two-sided and three-sided wraps, respectively.

Step 5: Based on the system selected, compute εfe and spacing, sf, using Equation (12),

$$s_f = \frac{A_{vf} E_f \varepsilon_{fe} (\sin\beta + \cos\beta) d_{fv}}{V_f} < w_f + \frac{d_{fv}}{4} \leq 24\ in. \quad (12)$$

Again, if the composite is placed in vertical strips, (sin β+cos β)=1.

5. Conclusions

This paper has reviewed various shear-strengthening methods, emphasizing the use of fiber-reinforced polymers (FRP). The ACI 440.2R guidelines offer a comprehensive framework for FRP-based shear strengthening. To effectively enhance the shear strength of RC beams with FRP, it is essential to estimate the composite's shear force contribution accurately. Another vital process is the Selection the appropriate FRP wrapping system, whether it be two-sided, three-sided, or fully wrapped. Additionally, determining the optimal spacing between FRP strips is crucial to ensure the success of the strengthening process. This targeted approach to shear strengthening increases the load-bearing capacity of RC beams and mitigates the risk of brittle shear failures, contributing to the longevity and resilience of RC structures.

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