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Low-Cost Glass Fiber-Reinforced Polymer Composite Wraps for Strengthening Deep Beams with and without Longitudinal Openings

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Abstract

This is a preliminary work on the application of low-cost glass fiber-reinforced polymer composites (Lo-Gs) wraps to enhance the structural response of shear-critical deep beams with and without openings. This study explores the performance of nine deep beams divided into three groups depending on the existence and number of longitudinal openings: solid section beams (Group 1), beams with one opening (Group 2), and beams with two openings (Group 3). Each group consisted of one unstrengthened beam and two beams strengthened with either one or two layers of Lo-Gs wraps. The results showed that Lo-Gs confinement effectively delayed failure in strengthened beams, while having minimal impact on the sudden failure behavior of unstrengthened specimens. Solid section beams exhibited peak load increases of 12.1% and 20.2% with one and two wraps, respectively. In contrast, beams with openings demonstrated higher but more variable strength gains. The presence of longitudinal openings diminished the effectiveness of the wraps in improving ultimate deflection and energy dissipation. While solid beams achieved up to a 130.1% increase in energy dissipation, beams with one and two openings showed lower gains of 63.4% and 57.0%, respectively. Existing design models, calibrated for synthetic FRPs, poorly predicted the behavior of beams with Lo-Gs wraps and neglected the effects of openings, emphasizing the need for further research and model development to address these limitations.

Keywords: Deep beams; Shear; Low-cost; Strengthening; Model evaluation.
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1. Introduction

Reinforced concrete (RC) deep beams, recognized by their low shear span-to-effective depth ratio (a/d), are capable of withstanding significant shear forces.[1] The structural safety of these beams depends on careful design and effective strengthening strategies. Critical factors affecting their reinforcement include the concrete's compressive strength, the shear span-to-depth ratio, the vertical and horizontal shear reinforcement ratios, the choice of strengthening materials, the number of layers applied, and the spacing of these layers.[2,3] The structural response of deep beams remains complex and somewhat unpredictable despite extensive experimental research conducted over the years[4] Studies have consistently shown that shear capacity plays a key role in the failure of deep beams, making it a key factor in evaluating their structural behavior and safety[4] Deep beams exhibit nonlinear deformation, strains, and non-flexural behavior, which deviate from conventional beam theories.[5] The elastic theory is not relevant to analyze deep beams since plane sections no longer remain plane after concrete cracking.[6] Structurally, load transfer in deep beams appears primarily through concrete struts, with supports creating an arching role, resulting in enhanced shear strength.[7]

Openings are often introduced in deep beams to allow for utilities like conduits, air conditioning systems, electrical wiring, and computer network cables.[8] However, when these openings disrupt the load path between the loading and reaction points, the load transfer mechanism becomes more complex, leading to a drop in shear capacity.[9] Despite the significant impact of openings on the structural response of deep beams, there remains a lack of clear design guidelines specifically addressing this issue.[10] The addition of openings

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in RC beams has raised significant concerns regarding their structural performance and functionality.[11] These openings complicate the otherwise straightforward load-bearing behavior of beams.[12] Sudden changes in cross-sectional dimensions around the openings result in stress concentrations at the corners, potentially causing wide cracks that compromise both the aesthetics and durability of the structure.[13] Additionally, openings in the web section of RC beams reduce stiffness, leading to increased cracking and distortions, which adversely affect the beam's strength and stability.[14,15] The drop in cross-sectional area alters the simple structural behavior of the beam, making it more complex.[16] To restore the load-carrying capacity of RC deep beams with openings, it is essential to strengthen the areas surrounding these openings. Proper construction and regular inspection of RC beams with openings are crucial to ensure their strength and stability, thereby minimizing potential structural deficiencies.[17,18]

The shear response of deep beams significantly influences internal stress distributions within the structure. In shear-dominated regions, compression develops in one direction while tension emerges in the perpendicular, vertical direction.[19] As the beam depth increases, the likelihood of sudden failure due to shear behavior becomes more pronounced.[20] This is particularly concerning for larger deep beams, where their brittle nature leads to more extensive crack propagation compared to smaller deep beams.[21] Failures in deep beams typically result from concrete crushing in the compression zones near the supports or along the occurrence of shear cracks.[21] Khaldoun and Khaled[22] investigated deep beams with a span-to-depth ratio of 2.5, finding some reserve strength in the post-cracking phase, which contributed to less brittle failure behavior.[19] Ashour and Morley[23] highlighted the significant impact of the span-to-depth ratio on load-carrying capacity, noting that horizontal and vertical web reinforcement plays a critical role. Notably, horizontal shear reinforcement has been shown to be more useful than vertical reinforcement in deep beams.[24] Russo *et al.*[25] proposed a shear strength expression for deep beams based on the strut-and-tie model, identifying diagonal struts, longitudinal reinforcement, vertical stirrups, and horizontal web reinforcement as key factors influencing shear capacity. Further studies by Nair and Kavitha[26] compared deep beams with circular and square openings, designed using the strut-and-tie model, through finite element analysis. Experimental results revealed that beams with circular openings exhibited superior shear resistance compared to those with square openings.

Many older structures, designed according to outdated standards, fail to meet current design codes, raising concerns about their safety and performance. Furthermore, prolonged exposure to environmental factors has led to the deterioration of numerous concrete structures, compromising their structural integrity. To address these issues, strengthening has emerged as a practical and cost-efficient alternative to rebuilding, which demands substantially more time and resources. Traditional methods such as steel plate bonding, ferrocement application, or increasing the cross-sectional dimensions of elements have been widely utilized for structural rehabilitation. However, experimental research[27] has demonstrated that fiber-reinforced polymers (FRPs) offer significant advantages over conventional techniques. Among various FRP options, carbon fiber-reinforced polymer (CFRP) composites are frequently preferred due to their lightweight properties, ease of installation, durability, high strength, resistance to corrosion, and suitability for on-site applications.[28] FRPs have become widely employed in civil engineering for the strengthening and rehabilitation of RC elements[29] Recent research and projects have focused on utilizing FRP materials for the effective restoration of structural performance in RC components.[30–34] Among the various types of FRPs, CFRP is the most commonly used, while glass, aramid, and basalt FRPs are increasingly gaining attention. These materials are highly valued for their exceptional strength, elasticity, durability, resistance to magnetic and chemical effects, and their ability to enhance energy dissipation and overall structural performance. Additionally, their practical benefits—such as ease of storage, application, and transportation—further contribute to their growing popularity in strengthening applications.[35–39] Synthetic FRPs are costly, at approximately 150 USD per square meter per layer, and energy-intensive to produce, consuming 300 gigajoules of energy per ton compared to just 5 gigajoules for natural hemp fiber.[40] This results in high carbon emissions, with one ton of CFRP releasing 29,500 kg of CO_2, significantly more than natural fibers like hemp, which emit only 410 kg per ton.[41] Additionally, synthetic FRP production generates hazardous, non-recyclable byproducts, posing environmental and health risks.[42–45] Despite these concerns, construction accounts for 10% of global FRP use.[46]

Yoddumrong *et al.*[47] studied the use of low-cost glass fiber-reinforced polymer composites (Lo-Gs) for the seismic strengthening of reinforced concrete (RC) columns. These composites, composed of bi-directional glass fiber sheets bonded with economical resin, typically used in the boat manufacturing industry, provide a budget-friendly alternative. While their tensile strength is around 350 MPa, which is lower than that of conventional GFRP (≈2500 MPa) and CFRP (≈4000 MPa), they offer a practical and economical option for structural retrofitting.[48] Lam *et al.*[49] demonstrated that integrating Lo-Gs with mechanical anchors significantly improved the load-carrying capacity and stiffness of deep RC beams. Moreover, Lo-Gs have also been employed to enhance the mechanical properties of concrete,[50] enhance beam

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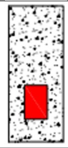
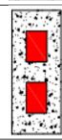
Table 1: Summary of the deep beam specimens.

Group	ID	Opening	Strengthening	Cross-Sectional Shape
1	DB-NO-CON	Nil	Nil	
	DB-NO-1G	Nil	1 Wrap	
	DB-NO-2G	Nil	2 Wraps	
2	DB-1LO-CON	One	Nil	
	DB-1LO -1G	One	1 Wrap	
	DB-1LO -2G	One	2 Wraps	
3	DB-2LO-CON	Two	Nil	
	DB-2LO -1G	Two	1 Wrap	
	DB-2LO -2G	Two	2 Wraps	

flexural performance,[51] and strengthen non-ductile bridge piers.[52] It is noted that Ls-Gs is locally available in Thailand and costs less than 3 USD per square meter.[47] Whereas the cost of a synthetic CFRP in Thailand might reach as high as 150 USD per square meter per layer.[40] Current review on literature shows that very few works have been performed to explore the response of deep beams with longitudinal openings. Ismail el-kassas *et al.*[53] tested deep beams of self-compacted concrete, by employing longitudinal openings of different size and shapes. The experimental results proven that longitudinal openings decreased the peak load of deep beams. Larger openings further reduce capacity, and openings in the compression zone cause a greater drop than those in the tension zone while the shape of the opening has little impact. Al-Khuzaie and Al-Yassri[54] investigated the response of reinforced self- compacting concrete deep beams with longitudinal circular openings of varying sizes. They tested six specimens, including one solid beam, and examined crack patterns, deflection, and load capacity. The study found that larger openings reduced load capacity, while steel pipe reinforcement improved stiffness and increased the ultimate load by 12.33% compared to unreinforced beams. Al-Hassany and Al-Yassri[55] investigated the structural response of deep beams with longitudinal openings reinforced by steel pipes. Ten specimens were tested, including one solid reference beam, with variables such as opening shape (circular, square, rectangular), size (3 sizes of circular openings), and void ratio. The findings showed that beams with circular openings performed similarly to the reference beam, with a load efficiency of 103%. Beams with square and rectangular openings had reduced load capacities (81% and 35%, respectively), with rectangular openings leading to early failure. Abdulabbas and Ismael[56] investigated the structural response and sustainability of hollow RC deep beams, focusing on the number and location of the hollows. Six hollow concrete beams were tested, along with one solid reference beam. Results showed that increasing the number of hollows reduced cracking flexural load, shear crack load, failure load, and stiffness. Changing the hollow location also decreased these parameters. Previous works on RC beams with longitudinal openings are very limited. This is a novel work that addresses the issue related to the brittle behavior of deep beams, especially in the presence of longitudinal openings. Previously, it was found that the square-shaped

Table 2: Summary of the peak load, ultimate deflection, and dissipated energy.

ID	Peak Capacity (kN)	Increase in Peak Capacity (%)	Ultimate Deflection (mm)	Increase in Ultimate Deflection (%)	Dissipated Energy (kN-mm)	Increase in Dissipated Energy (%)
DB-NO-CON	234.9	-	7.0	-	1087.4	-
DB-NO-1G	263.3	12.1	9.9	41.4	2081.0	91.4
DB-NO-2G	282.3	20.2	11.2	60.0	2502.5	130.1
DB-1LO-CON	166.2	-	4.5	-	491.0	-
DB-1LO -1G	209.9	26.3	5.1	13.3	733.0	49.3
DB-1LO -2G	219.6	32.1	5.5	22.2	802.4	63.4
DB-2LO-CON	137.1	-	3.4	-	204.5	-
DB-2LO -1G	162.7	18.7	3.5	2.9	296.2	44.4
DB-2LO -2G	192.7	40.5	4.0	17.6	321.3	57.0

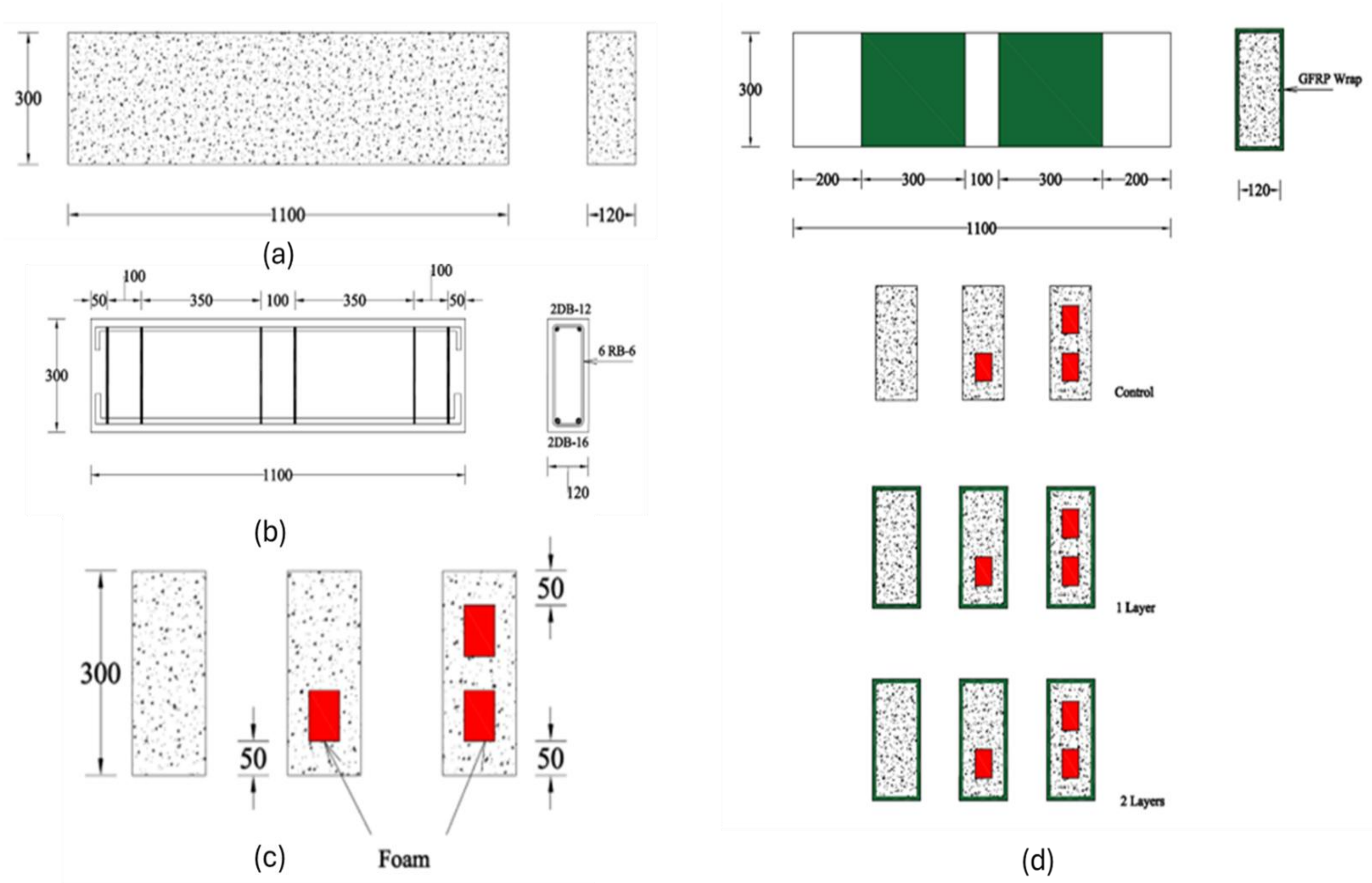


Fig. 1: A typical deep beam with: (a) beam details and (b) steel bar details, (c) opening details, and (d) strengthening details. (Units are in mm).

openings result in more reduction in the capacity. This work explores the behavior of deep beams with rectangular openings, considering their number as a parameter. Additionally, the low-cost solution of Lo-Gs is proposed to enhance the shear capacity of deep beams with longitudinal openings. Therefore, the quantity of the Lo-Gs wrap confinement is explored in this study as well.

2. Details of experimental program

2.1 Summary of beam specimens

This program comprised nine deep beams. Three groups were formed, as shown in Table 1, based on the existence and number of longitudinal openings. Each group involved three beams. One beam was tested without strengthening, whereas the other two beams were strengthened with one or two Lo-Gs wraps. Beams in Group 1 did not include a longitudinal opening. A single rectangular longitudinal opening was provided in Group 2 beams, while Group 3 beams were constructed with 2 rectangular longitudinal openings. This study identified each beam with a particular nomenclature consisting of three parts. The first part, i.e., "DB", denoted the deep beam specimen type. The second part identified the presence or number of longitudinal openings. That is, NO, 1LO, and 2LO denoted the cases of no opening, one opening, and two opening, respectively. The last part stated the presence or quantity of Lo-Gs wraps. As in, CON, 1G, and 2G denoted no strengthening, one-layer strengthening, and two-layer strengthening, respectively.

2.2 Details of deep beams

Each beam tested in this work had a height and width of 300 mm and 120 mm, respectively (Fig. 1). For beams in Group 2, the sole longitudinal opening was rectangular in shape, located at a height of 50 mm from the bottom face. The size of the opening was 50 mm × 30 mm. Two longitudinal openings were provided in Group 3 beams, placed vertically. The size of the openings was similar to the opening in Group 1 beams, with the bottom opening placed concentrically with the opening in Group 2 beams. The second opening was located at a distance of 50 mm from the top face, as shown in (Fig. 1) The structural detailing is also displayed in (Fig. 1). The tension reinforcement comprised two deformed bars having a diameter of 16 mm. Two deformed bars of 12 mm diameter were employed as the top reinforcement. The transverse reinforcement involved 6 mm plain bars provided only near the supports and under the load. Stirrups were not provided within shear spans to identify the role of Lo-Gs wraps in shear strength upgradation. The length of each beam was 1100 mm.

2.3 Material properties

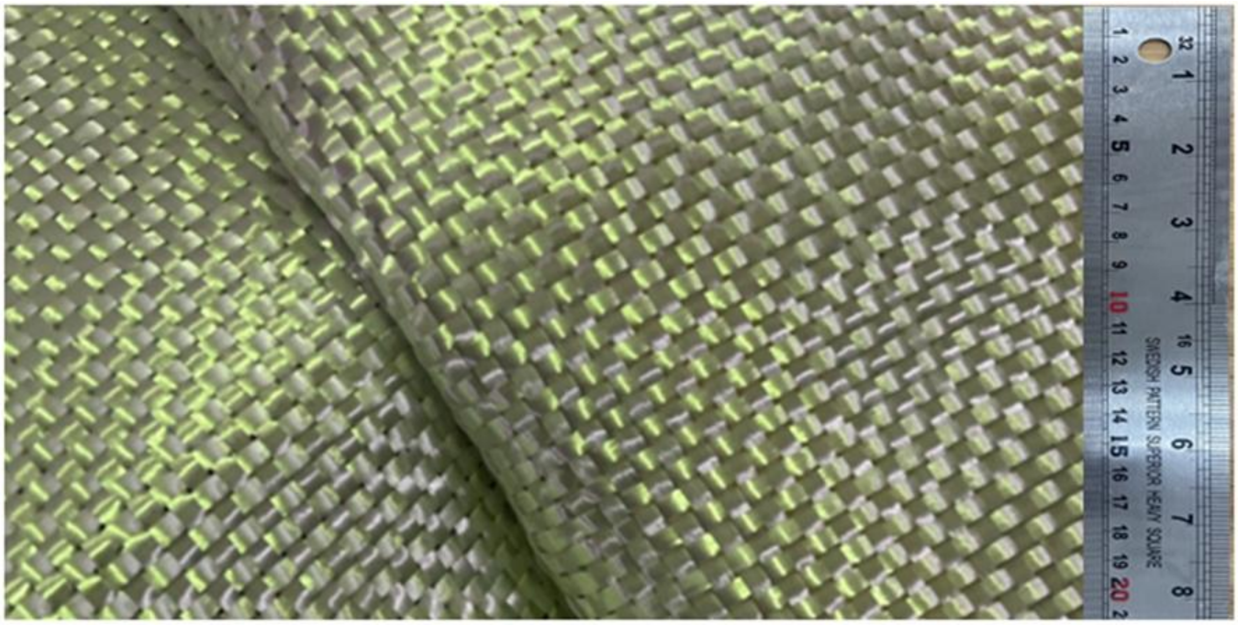


Fig. 2: Typical Lo-Gs employed in this work.

The target compressive strength of the concrete at 28 days was designed to reach 20 MPa. The bottom longitudinal reinforcement had yield and ultimate strengths of 400 MPa and 500 MPa, respectively, while the top reinforcement demonstrated corresponding values of 450 MPa and 550 MPa, measured by following ASTM E8.[57] Recent research by Yoddumrong *et al.*[47] proposed the use of Lo-Gs as a method to enhance the seismic performance of reinforced concrete columns. These Lo-Gs, commonly used in boat construction, are readily available and feature bi-directional glass fiber sheets combined with an affordable resin matrix. Recognized for their cost efficiency and sufficient tensile properties, Lo-Gs are a practical material option. The mechanical properties of Lo-Gs sheets were evaluated following ASTM D7565.[58] The elastic modulus, tensile strength, and rupture strain of Lo-Gs sheets were 18.7 GPa, 377.0 MPa, and 2.035%, respectively. The thickness of Lo-Gs sheets was 0.50 mm. Fig. 2 provides an example of typical Lo-Gs sheets, where the fibers exhibit a random orientation.

2.4 Construction and strengthening of beams

The steel reinforcement cage was first assembled outside the formwork. To ensure a consistent 16 mm clear cover on all sides, spacers were accurately positioned within the formwork before placing the cage. Square and rectangular Styrofoam inserts were incorporated into the cage to form the required openings. Concrete was poured with the beams positioned horizontally, and after a standard 28-day curing period, the proposed Lo-Gs confinement technique was applied. This confinement targeted the shear spans of the beams, as shown in Fig. S1. The Lo-Gs sheets were installed using the wet lay-up method,[59] beginning with thorough surface cleaning and

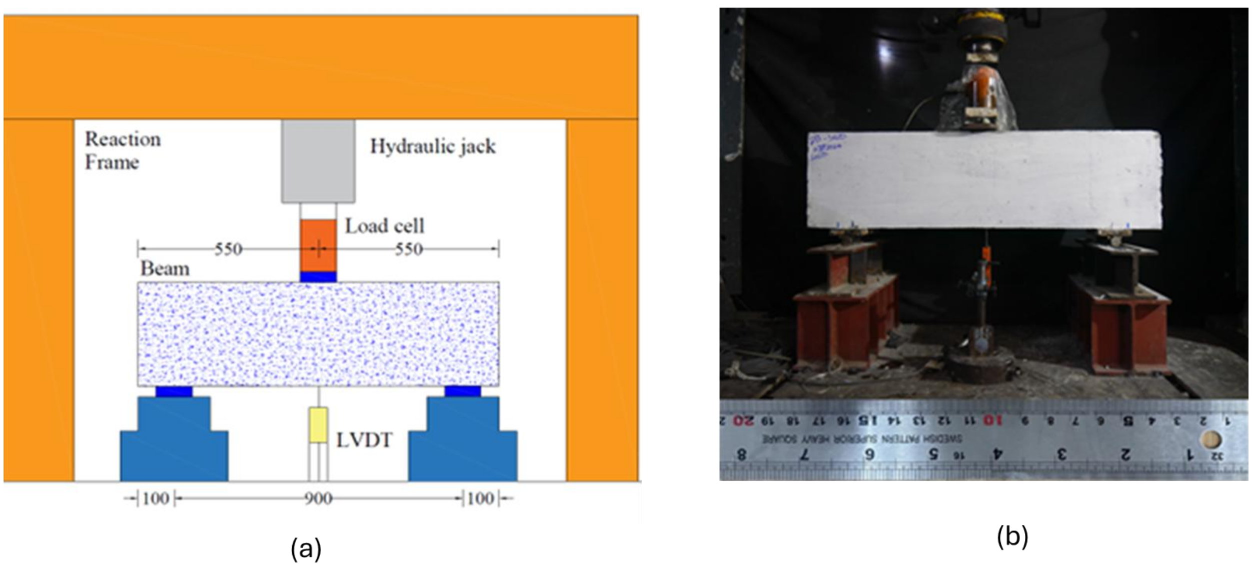


Fig. 3: Typical test setup adopted in this work, a) schematic, and b) lab testing. (Note: All units are in mm)

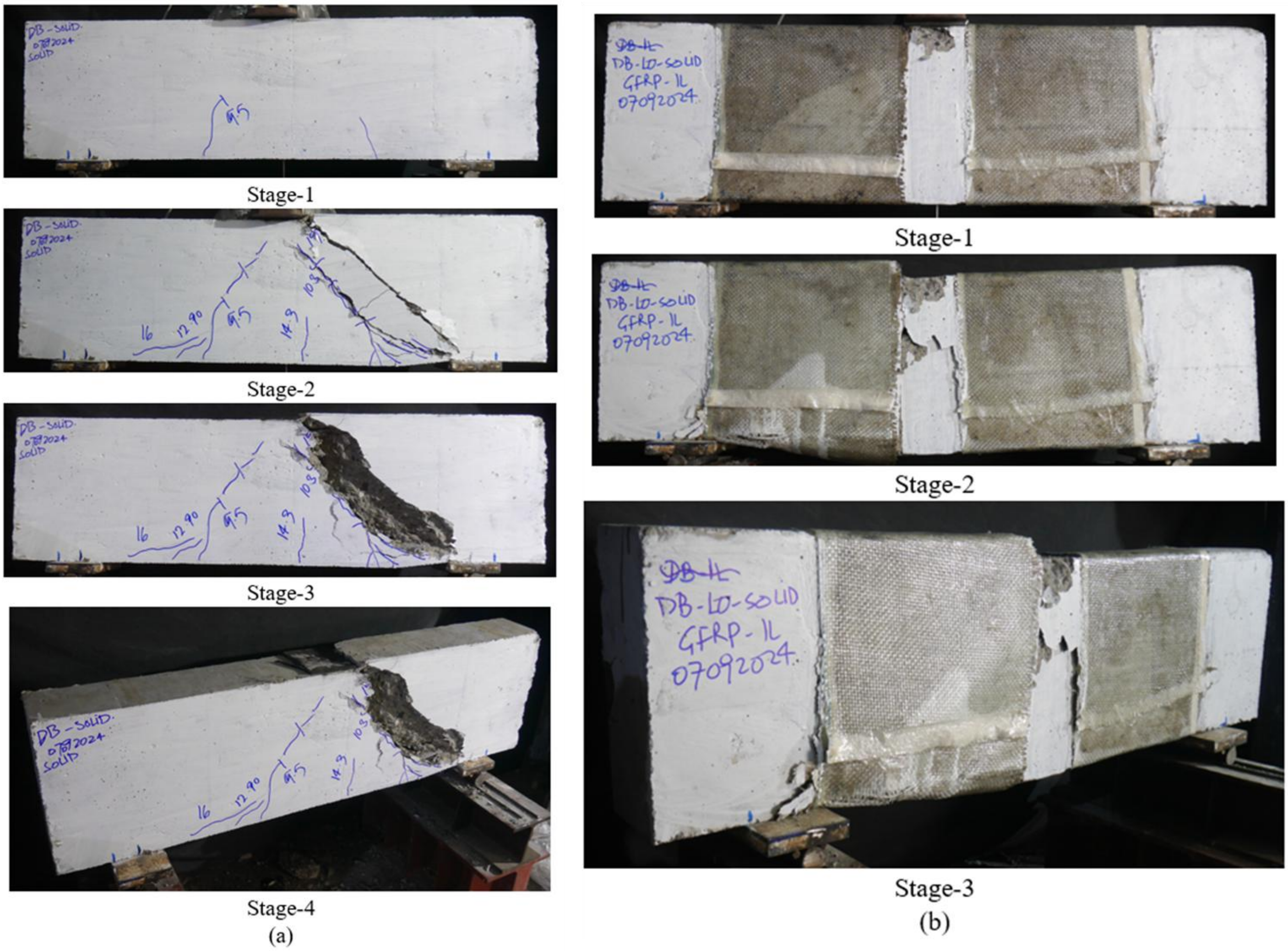


Fig. 4: Failure mode of Group 1 beams: (a) DB-NO-CON (sudden, shear-dominated failure), (b) DB-NO-1G. (delayed failure, no debonding, vertical cracking in conjunction with inclined cracks).

application of polyester resin to promote adhesion. The first layer of Lo-Gs sheet was applied and saturated with resin, and for beams requiring two layers, the procedure was repeated to ensure proper strengthening.

2.5 Test setup

Fig. 3 presents the experimental setup, in which each beam was subjected to a three-point bending test until failure. The clear span between supports was maintained at 800 mm. Mid-span deflection was measured using a displacement transducer placed at the beam's center. To ensure uniform load distribution, 25 mm thick and 150 mm wide steel plates were placed beneath the loading point and above the supports. Crack initiation and propagation were closely monitored and documented, and the failure modes were recorded. Loading was applied incrementally using a 500 kN capacity hydraulic jack. A load cell was used to measure the applied force at each increment, while a data logger simultaneously recorded both the load and the corresponding deflection.

3. Experimental results

3.1 Failure patterns of beams

The failure of beams in Group 1 is illustrated in Fig. 4 and S2 The failure of the control beam DB-NO-CON was sudden and abrupt, as characteristically known for a shear-dominated phenomenon. Initially, vertical cracks emerged at the bottom that slowly propagated toward the mid-height while changing direction to an oblique angle. Suddenly, the right-hand side crack widened and propagated towards the loading point. Finally, the beam failed in a sudden manner without undergoing noticeable vertical deflection. The type of the major diagonal crack exhibited by this beam (see Fig. 4a) denotes that the load was mainly carried by the compressive strut, as reported by Yang *et al.*[60] as well. The strengthened beams in Group 1 were failed by demonstrating concrete crushing under the load and near supports. In addition, the fracture of Lo-Gs wraps was noted that highlighted the effectiveness of the wet layup process adopted, by eliminating the premature failure through debonding. The failure of the strengthened beams in Group 1 also showed diagonal cracking. However, noticeable vertical deformation was also observed, indicating a delayed failure, highlighting the effectiveness of

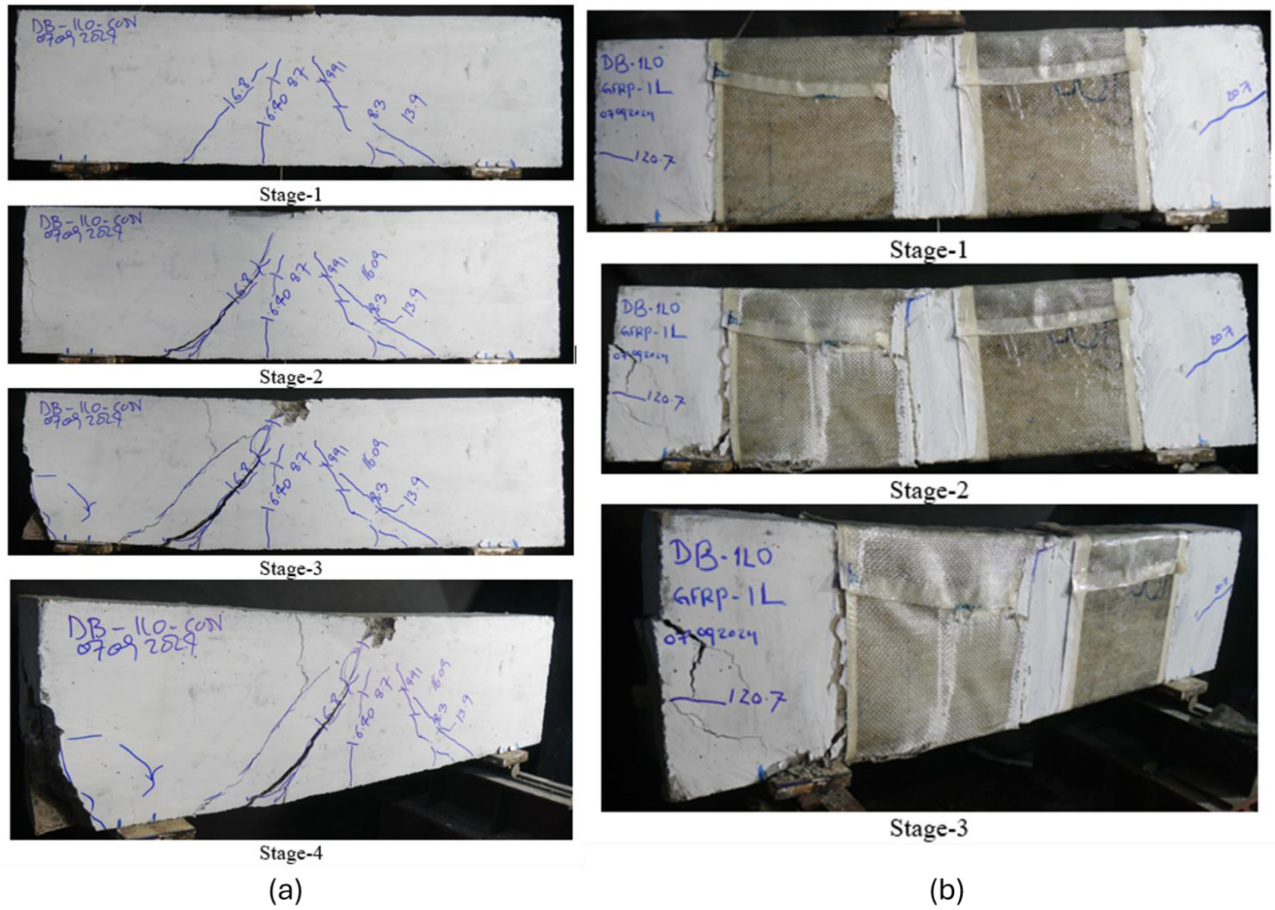


Fig. 5: Failure mode of Group 2 beams: (a) DB-1LO-CON (sudden, shear-dominated failure), (b) DB-1LO-1G. (delayed failure, no debonding, vertical cracking in conjunction with inclined cracks).

Lo-Gs wraps.

The failure of beams in Group 2 is shown in Fig. 5 and S3 couple of flexural cracks appeared earlier in the loading stage of Beam DB-1LO-CON. However, these cracks remained restricted in height. The formation of the diagonal cracks near supports resulted in the formation of the so-called compression strut, as shown in Fig. 5a, resulting in a sudden failure. The work by El-Kassas[53] on deep beams with longitudinal openings also showed that the presence of longitudinal openings did not influence the formation of compression struts that are often reported for the solid section deep beams. The strengthened beams, similar to Group 1, demonstrated a delayed failure, characterized by concrete crushing under load, separation of concrete wedges near supports, and fracture of wraps.

It was observed in the case of beam with two longitudinal openings, indicating that the number of openings did not change the load paths that are typically recognized in solid section deep beams. The strengthened beams in Group 3 did not show significant deformation, as reflected from the absence of noticeable vertical cracking. This can be attributed to the significant drop in the cross-section of the beam, resulting in a further drop of load. Further adding to this, the application of external confinement seems less effective in the presence of longitudinal openings. Previous works on deep beams[61,62] with web openings have highlighted the change in the load path if openings are placed within shear span. The current study suggests that a longitudinal opening did not influence this load path (Fig. 6 and S4).

3.2 Load vs. deflection response

Fig. 7 presents the measured load-deflection response of beams in all groups. All beams demonstrated a linear ascending branch till the cracking load. Subsequent to that, a slight reduction in the elastic stiffness was observed. Within this stage, flexural cracks started to occur. As shown in, Fig. 7a, a notable improvement in the load capacity was observed for solid section beams due to the Lo-Gs wrapping. The control beam showed a sudden drop in load, whereas the strengthened beams were able to maintain the peak load till noticeable deformation. The presence of longitudinal openings also influenced the effectiveness of external confinement. As shown in, Fig. 7b strengthened beams could not maintain their peak loads, resulting in an abrupt drop. An even more severe response was observed for the case of two longitudinal openings, as shown in Fig. 7c. On the contrary, previous works [61] have shown that the existence of a web opening does not impact the load carrying capacity significantly.

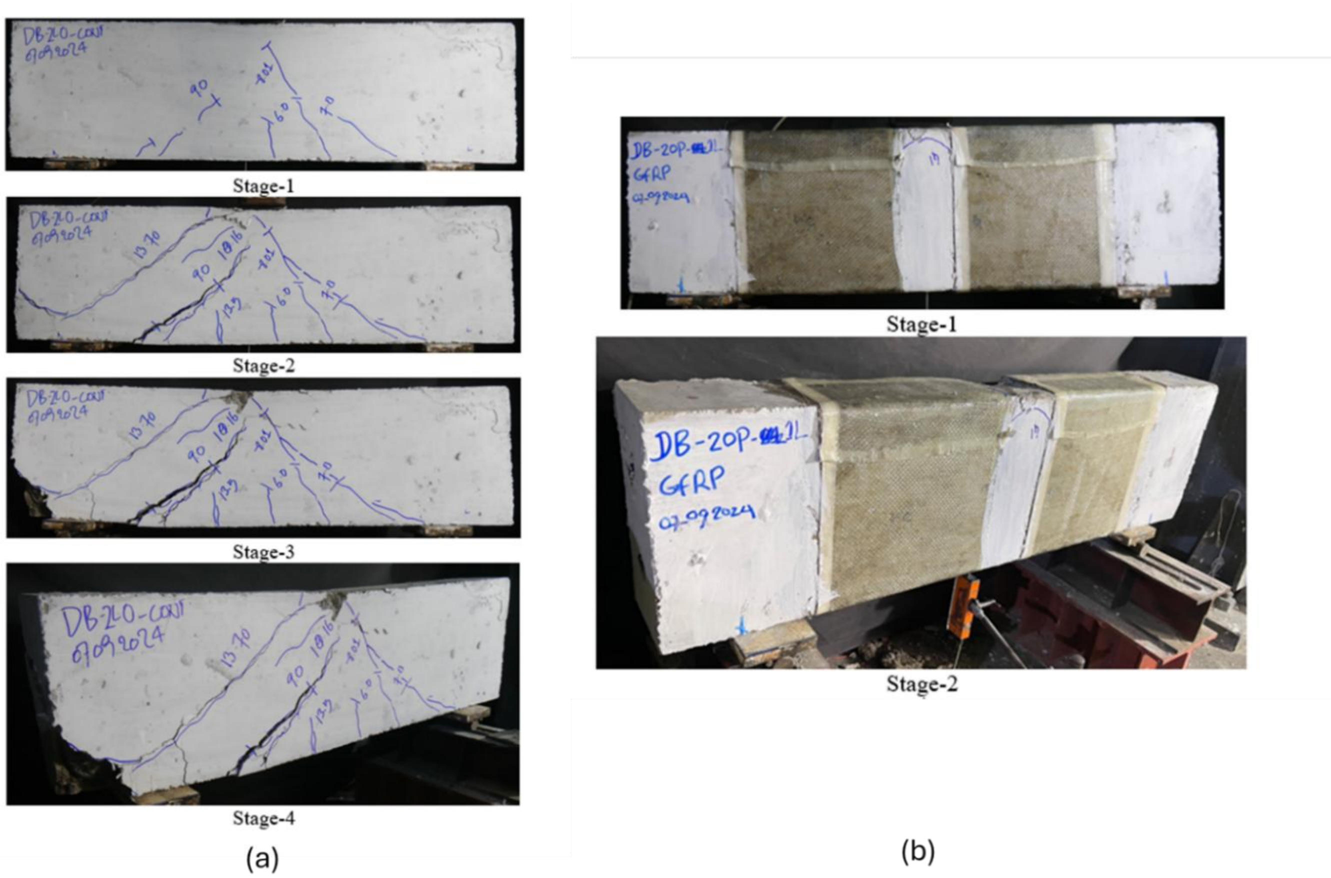


Fig. 6: Failure mode of Group 3 beams: (a) DB-2LO-CON, (b) DB-2LO-1G, and (c) DB-2LO-2G.

3.3 Peak capacity, ultimate deflection, and dissipated energy

The summary of the peak load and ultimate deflection is presented in Table 2. Noticeable upgradation in the peak load and ultimate deflection was observed. Notably, the ultimate deflection was taken as the deflection that corresponds to a 20% drop in the peak load. The solid section beams with one and two Lo-Gs wraps showed a 12.1% and 20.2% improvement in their peak loads, respectively. Beams with one longitudinal opening and strengthened with one and two Lo-Gs wraps showed peak load improvements of 26.3% and 32.1%, respectively. This improvement was 18.7% and 40.5%, respectively, for beams with two longitudinal openings and strengthened with one and two Lo-Gs wraps. The dissipated energy showed improvements of up to 130.1%, 63.4%, and 57.0%, respectively, for solid section, one longitudinal opening, and two longitudinal openings. The authors observed that the quantity of Lo-Gs wraps positively influenced the performance of deep beams, with and without openings. That is, a positive correlation exists between the quantity of Lo-Gs wraps and the improvement in structural performance. However, it was noted that this relation is not linear and the improvement due to two Lo-Gs wraps, in general, was not as high as that imparted by a single Lo-Gs wrap.

3.4 Effect of the longitudinal opening

Fig. 8 presents the effect of the presence of longitudinal opening on the effectiveness of external confinement, showing that Lo-Gs wraps performed slightly better than on beams with longitudinal openings in terms of the peak load improvement. However, the same was not true in the case of ultimate deflection. The increase in ultimate deflection was 41.4% and 60.0%, respectively, for solid section beams with one and two Lo-Gs wraps. This improvement dropped to 13.3% and 22.2%, respectively, for the case of one longitudinal opening. A further drop to 2.9% and 17.6% was noted in the case of two longitudinal openings. This suggests that the provision of a longitudinal opening negatively affects the effectiveness of Lo-Gs wraps to allow for large deformations. The dissipated energy by the beams was calculated by determining the area under the load-deflection curves. However, this area beyond the ultimate deflection was neglected. Table 2 shows that dissipated energy follows a similar trend as that by the ultimate deflection. For solid section beams, dissipated energy was improved by up to 130.1%. While this improvement dropped to 63.4% and 57.0% for deep beams with one and two longitudinal openings, respectively.

4. Prediction assessment of shear strength enhancement by Lo-Gs wraps

4.1 Current shear strength expressions

The total shear strength V_t of RC beams strengthened with FRPs is generally calculated as the sum of the contributions from the concrete V_c the transverse reinforcement V_s, and the

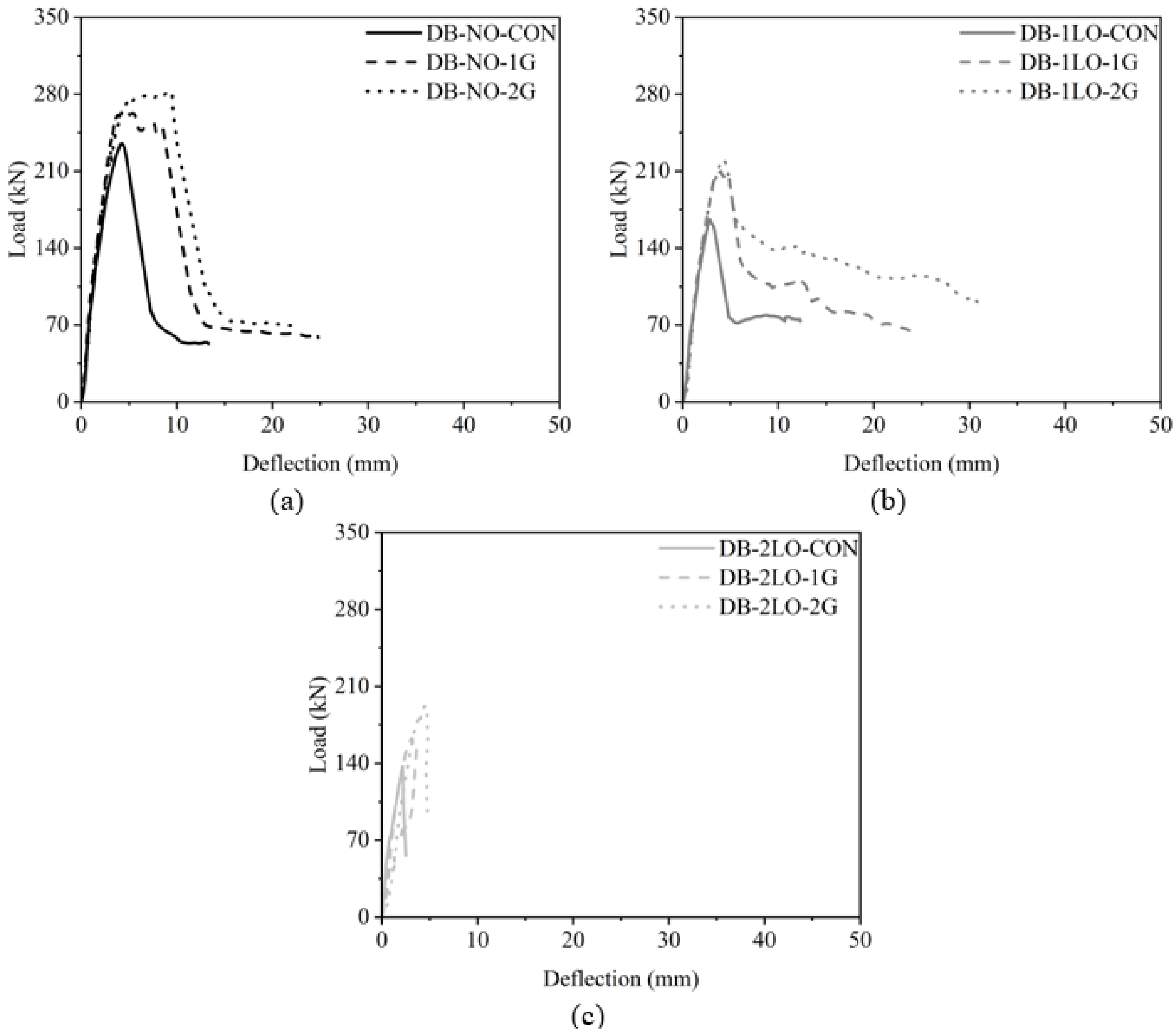


Fig. 7: Load-deflection response of beams in: (a) Group 1, (b) Group 2, and (c) Group 3.

FRP V_f:

$$V_t = V_c + V_s + V_f \quad (1)$$

Since no shear reinforcement was provided, the term V_s was neglected. Thus, the experimental contribution to total shear strength by Lo-Gs wraps was determined by subtracting the shear capacity of control beams from the total shear capacity of strengthened beams.

• According to Khalifa *et al.*,[63] the shear strength of a deep beam contributed by FRPs may be determined by:

$$V_f = \rho_f E_f \epsilon_{fe} b_w d_f (1 + cot\beta) sin\beta \quad (2)$$

where E_f denotes the elastic stiffness of FRP, d_f is the depth of FRP, ϵ_{fe} is the effective rupture strain capacity of FRP, and ρ_f denotes the volumetric ratio of FRP. The term b_w denotes the width of the section, while β is an angle that comes into play in the case of inclined FRP application. The volumetric ratio of FRPs is determined by:

$$\rho_f = \frac{2 n_f t_f w_f}{b_w s_f} \quad (3)$$

where the volumetric ratio involves thickness, quantity, width, and spacing of FRP represented by t_f, n_f, w_f, and s_f, respectively.

• Triantafillou[64] demonstrated that the effective strain in externally bonded FRP sheets or strips is affected by their axial rigidity ($\rho_f E_f$). Using experimental data, the effective strain was determined by back-calculating from the observed shear strength contribution (V_f). An empirical relationship was established by correlating the effective strain with axial rigidity based on test results from 40 beams documented in prior studies. Building on this approach, Khalifa *et al.*[63] analyzed a larger dataset of 48 beams, which included two types of FRP materials (Carbon and Aramid), three wrapping configurations (side-only, U-shaped, and full wraps), and both continuous and strip forms of FRPs. They introduced three equations for calculating the reduction factor (R_f), selecting the smallest value to estimate the effective strain (ϵ_{fe}). This strain value was then used in the shear strength computation of FRP-strengthened beams as per (Eq. (2)) Despite being derived from tests considering both FRP rupture and de-bonding failure modes, Khalifa *et al.*[63] recommended applying Eq. (4) predominantly for cases involving FRP rupture.

$$R_f = 0.5622(\rho_f E_f)^2 - 1.2188\rho_f E_f + 0.778 \quad (4)$$

Khalifa *et al.*[63] emphasized the importance of restricting the shear cracking width by imposing an upper limit of 0.5 on R_f.

- In 2002, Triantafillou and Antonopoulos[64] proposed three regression-based equations derived from the analysis of 75 experimental datasets. Two of these equations were tailored for CFRP wraps, while the third was specifically developed for fully wrapped Aramid FRP wraps. The equation corresponding to the fully wrapped CFRP wrap is given as:

$$\epsilon_{fe} = 0.17\left(\frac{f_c^{\frac{2}{3}}}{\rho_f E_f}\right)^{0.30} \epsilon_{fu} \quad (5)$$

The contribution of the FRPs to the overall shear strength is calculated by substituting the effective strain (ϵ_{fe}) determined from Eq. (5) into Eq. (2).

- In 2005, Zhang and Hsu[65] introduced two alternative equations for calculating the reduction factor (R_f). One of these equations accounted for the influence of concrete strength and was developed using regression analysis of experimental data, as expressed below:

$$R_f = 1.4871\left(\frac{\rho_f E_f}{f_c}\right)^{-0.7488} \quad (6)$$

- Zhang and Hsu[65] also derived an analytical expression for R_f based on a detailed analysis of the bonding mechanism. The expression is presented as follows:

$$R_f = \frac{\tau_{max} L_e}{2} f_{fu} t_f \leq 1 \quad (7)$$

where τ_{max} is the ultimate direct shear strength measured using Eq. (9); and L_e is presumed to be 75 mm.

$$\tau_{max} = (7.64 \times 10^{-4} f_c^2) - (7.64 \times 10^{-2} f_c) + 6.38 \quad (8)$$

The minimum R_f value derived from Eq. (6) and (7) is used to calculate the effective tensile strain in the FRP. Furthermore, Zhang and Hsu[65] suggested a maximum R_f value of 0.4. They also proposed an equation analogous to Eq. (2) for calculating the FRP's shear strength contribution V_f. For a continuous FRP sheet, the shear strength contribution was expressed as:

$$V_f = w_{fe} t_f f_{fe} \sin^2\beta \leq \left(\frac{2\sqrt{f_c} b_w d}{3} - V_s\right) \quad (9)$$

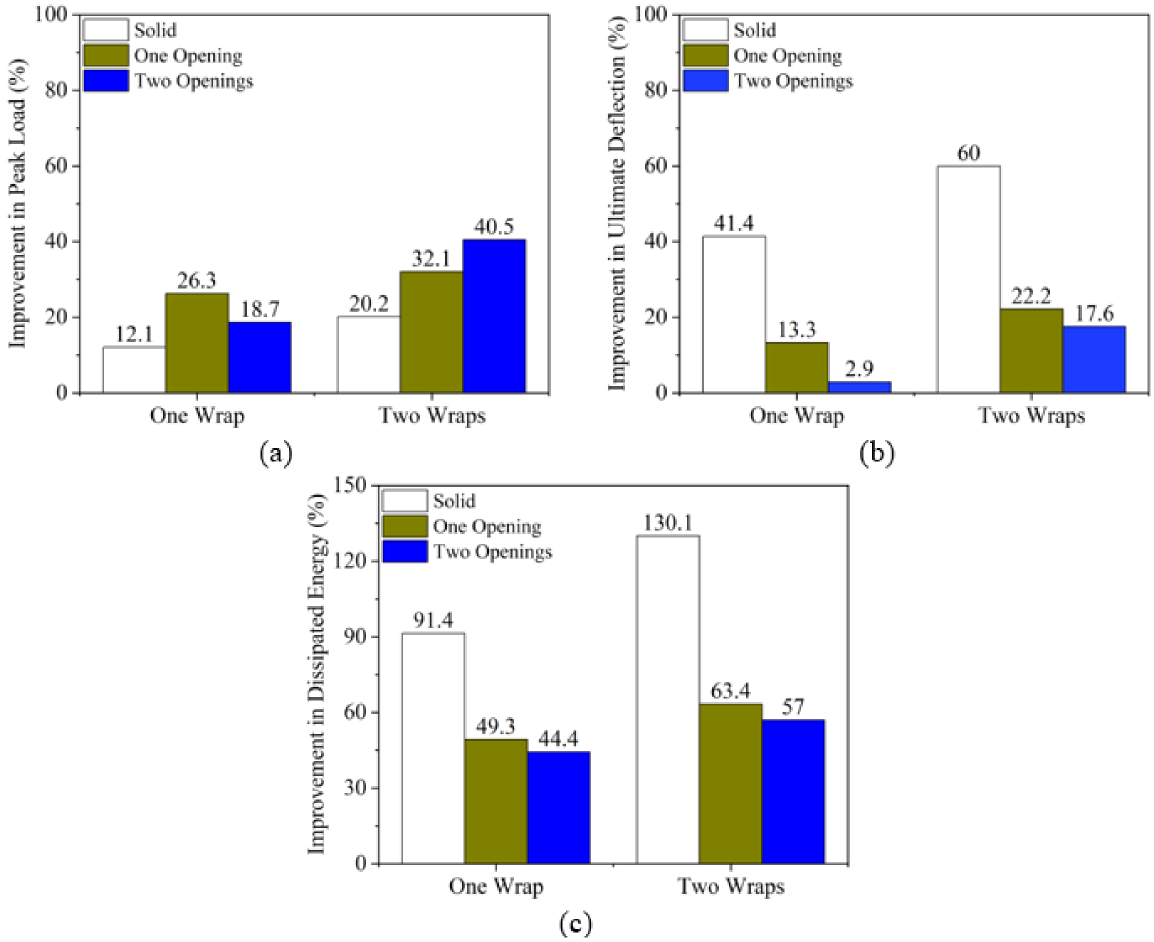


Fig. 8: Effect of the opening presence on improvement in: (a) peak load, (b) ultimate deflection, and (c) dissipated energy.

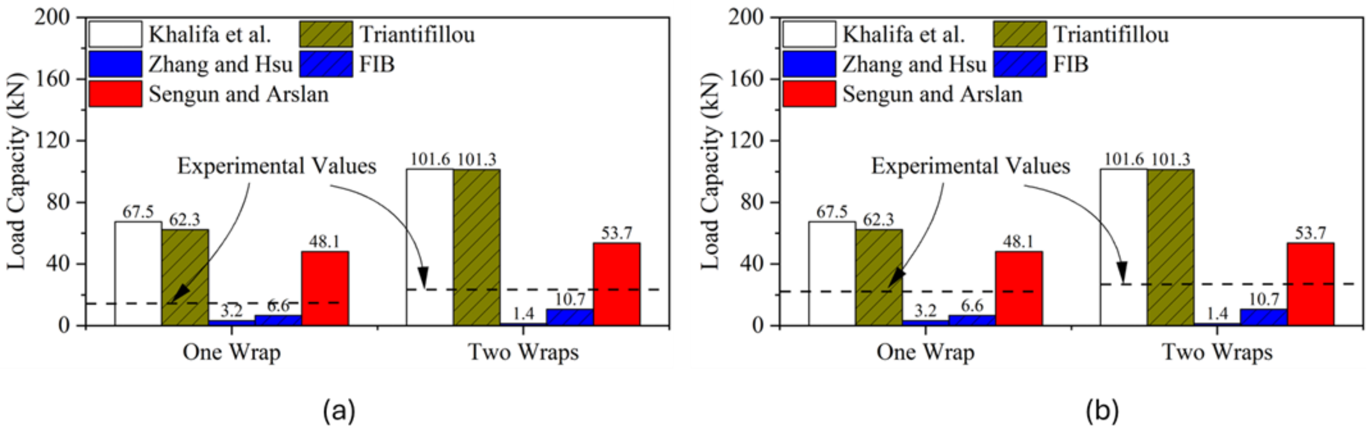


Fig. 9: Comparison of experimental vs predicted load capacity of beams in: (a) Group 1 and (b) Group 2.

where w_{fe} can be computed as:

$$w_{fe} = d_f - 2e^{\{6.134-0.58\ln(t_f E_f)\}} \tag{10}$$

- FIB[66] also presents an expression to estimate V_f given as:

$$V_f = 0.9\frac{2n_f t_f w_f E_f \epsilon_{fe} d_f}{s_f} \tag{11}$$

It is important to note that the ratio w_f/s_f becomes 1.0 in the case of continuous wraps. The effective strain in for FIB[66] Eq. (11) is denoted as:

$$\epsilon_{fe} = 0.8\left(0.17\frac{f_{cm}^{\frac{2}{3}}}{E_f \rho_f}\right)^{0.30}\epsilon_{fu} \tag{12}$$

where f_{cm} denotes the mean compressive strength of concrete.

- Sengun and Arslan[67] proposed the following expression for V_f:

$$V_f = \frac{2n_f t_f w_f E_f d_f}{s_f} \times 0.0018\left(E_f \rho_f\right)^{-0.84} \tag{13}$$

The comparison of experimental vs predicted load capacity of deep beams is shown in Fig. 9. For Group 1 beams, it is clear that none of the existing models closely predicted the response. This can be attributed to the sufficiently lower elastic modulus and tensile strength of Lo-Gs wraps than synthetic FRPs. The models by Khalifa *et al.*, Triantifillou, and Sengun and Arslan notably overestimated experimental results, whereas the models by FIB and Zhang and Hsu underestimated them. Since the existing expressions do not feature the effect of a longitudinal opening in beams, their predictions for Group 2 beams were also insufficient, as shown in Fig. 9(b). The provision of longitudinal openings in deep beams becomes inevitable in several cases. Consequently, there is a need for further studies in this domain to further and deeply explore their behavior. The current state-of-the-art on deep beams with longitudinal openings is extremely limited. Therefore, design models for deep beams should also be enriched with the option to consider the presence of longitudinal openings.

5. Conclusion

The study involved nine deep beams divided into three groups depending on the existence and quantity of longitudinal openings. Each group consisted of three beams: one un strengthened beam and two beams reinforced with either one or two Lo-Gs wraps. Group 1 beams had no longitudinal openings, Group 2 beams featured a single rectangular opening, and Group 3 beams were constructed with two rectangular longitudinal openings. The following important conclusions were drawn.

1. The application of Lo-Gs wraps had minimal impact on the failure mode of the un strengthened beam, which remained sudden and abrupt. However, the strengthened beams exhibited a significant delay in failure, accompanied by the rupture of the Lo-Gs wraps. Given that the confinement was limited to only two sheets, future studies should investigate the use of additional sheets, as the observed improvements in behavior were closely linked to the extent of confinement provided.

2. All beams showed a linear response until cracking, followed by reduced stiffness and flexural cracking. The control solid section beam experienced a sudden load drop, while strengthened beams maintained peak loads with deformation. However, longitudinal openings reduced confinement effectiveness, with abrupt load drops more severe in beams with two openings.

3. Solid section beams strengthened with one and two Lo-Gs wraps showed peak load increases of 12.1% and 20.2%, respectively. For beams with one longitudinal opening, the improvements were 26.3% and 32.1%, while those with two openings saw increases of 18.7% and 40.5%. Dissipated energy improved by up to 130.1% for solid beams, 63.4% for beams with one opening, and 57.0% for beams with two openings. The results indicate that increasing the number of

Lo-Gs wraps enhances performance, though the relationship is not linear, with the benefit of two wraps generally being less pronounced than that of a single wrap.

4. Lo-Gs wraps showed better peak load improvements in solid beams compared to those with longitudinal openings. However, this trend did not hold for ultimate deflection. This indicates that longitudinal openings reduce the ability of Lo-Gs wraps to accommodate large deformations. Dissipated energy followed a similar trend. Solid beams showed up to a 130.1% increase in dissipated energy, while beams with one and two openings showed reduced improvements of 63.4% and 57.0%, respectively.

5. For solid section beams, none of the existing models accurately predicted the response, likely due to the lower elastic modulus and tensile strength of Lo-Gs wraps compared to synthetic FRPs. Models by Khalifa *et al.*, Triantifillou, and Sengun and Arslan significantly overestimated the experimental results, while those by FIB and Zhang and Hsu underestimated them. Additionally, as existing models do not account for the impact of longitudinal openings and their predictions for beams with longitudinal openings were inadequate. Since longitudinal openings are often necessary in practice, further research is essential to better understand their behavior. The limited current knowledge highlights the need to develop design models that incorporate the effects of longitudinal openings in deep beams.

The proposed Lo-Gs-based solution in enhancing the shear capacity of deep beams is found effective. However, the durability of Lo-Gs wraps must be assessed in future studies. Moreover, fire performance of Lo-Gs should be carefully assessed and decided.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

CRediT Statement

Kittipoom Rodsin: Conceptualization, Analysis, Funding, Wirting and Editing Article. **Ali Ejaz:** Conceptualization, Investigation and Wirting and Editing Article. **Qudeer Hussain:** Conceptualization, Investigation and Wirting and Editing Article. **Songsak Suthasupradit:** Conceptualization, Investigation and Wirting and Editing Article. **Rattapoohm Parichatprecha:** Conceptualization, Analysis, Funding, Wirting and Editing Article. **Kriti Shrestha:** Conceptualization, Investigation and Wirting and Editing Article.

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