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Finite Element Analysis on Shear Performance of FSK Reinforced FRP-UHPC Composite Beams

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Abstract - The shear performance of fiber-reinforced polymer (FRP)-ultra high performance concrete (UHPC) composite beams with FRP shear key (FSK) was investigated through a refined finite element (FE) analysis. The comparison between the FE analysis and experimental results demonstrated a good agreement. Based on the validated model, a parametric analysis was conducted on the shear performance of FRP-UHPC composite beams with FSK, focusing on parameters such as concrete slab strength, height and width, FRP web height and thickness, and FSK spacing. The results indicate that increasing the strength and section size of the concrete slab can improve the flexural stiffness and the shear capacity of composite beams. The use of UHPC for concrete slabs can also effectively inhibit interface slip. Increasing the shear strength and thickness of FRP web can result in improved load carrying capacity and reduced deformation of composite beams. This can also lead to a shift in the failure mode from shear failure to bending failure. The reduction of FSK spacing can effectively enhance the shear performance of the interface, thereby improving the composite action and increasing the bearing capacity and deformation resistance of composite beams.

***Keywords*:** composite beams; ultra-high performance concrete; FRP profiles; FSK; shear performance

1. Introduction

In recent years, the field of structural engineering has been relentlessly seeking solutions characterized by high performance, extended longevity, and sustainability. The conventional reinforced concrete structures, however, have been encountered substantial challenges in the form of severe corrosion issues [1]. This predicament not only leads to structural deterioration and increased maintenance costs but also poses significant safety concerns. Against this backdrop, fiber reinforced polymer (FRP) and ultra-high performance concrete (UHPC) have emerged as promising alternatives. FRP profiles are widely utilized in structural engineering due to their merits such as high strength, lightweight nature [2], and excellent corrosion resistance [3]. UHPC represents an innovative cement-based composite material with excellent strength [4] and durability [5]. Therefore, the integration of FRP profiles with UHPC capitalizes on their complementary advantages, resulting in a novel structural system characterized by superior strength, enhanced durability, and reduced weight.

Until now, the examination of shear performance parameters for FRP-UHPC composite beams has been constrained by the limited number of studies conducted. Furthermore, the anisotropic nature of FRP introduces diversity and complexity into the failure modes of composite beams [6], thereby posing challenges to the development of system design techniques. Hence, further experimental research and parametric analysis are imperative to gain a comprehensive understanding of the shear performance of FRP-UHPC composite beams.

This paper presents a comprehensive study involving four-point loading tests and refined finite element (FE) analysis on four FRP-UHPC composite beams. Finite element models were developed using the concrete damaged plasticity model (CDPM) for damage evolution simulation of concrete and FRP profiles, along with the application of the Puck failure criterion. Additionally, a bilinear cohesive zone model (CZM) was adopted to simulate the mechanical behaviour of composite interfaces. Based on the validated model, a detailed parametric analysis of FRP-UHPC composite beams with FSKs was carried out. The findings of this study offer valuable theoretical insights for the structural design and practical implementation of FRP-UHPC composite beams.

2. Experimental overview

Zhang et al. [7] conducted four-point loading tests to investigate the shear behaviour on FSK reinforced FRP-UHPC composite beams. The dimensions of the specimens are illustrated in Fig. 1. The specimens have FRP profiles with dimensions of 180 × 100 × 10 × 10 mm ($h_{fw} \times b_f \times t_{fw} \times t_f$) and UHPC slab with cross-sectional dimension of 200 × 60 mm ($b_c \times h_c$). The dimensions of FSK are 3 × 40 × 40 mm ($t_s \times b_s \times h_s$) and the spacing is 200 mm.

The axial compressive and tensile strengths of UHPC are 93.6 MPa and 7.91 MPa, respectively. The GFRP profiles were manufactured by using the pultrusion process method. Symmetric and balanced laying plans were adopted for the fibers at the flange and web. The uniaxial tensile and compressive strength are 375 MPa and 328 MPa, respectively, while the tensile and compressive modulus of elasticity are 33.8 and 30.4 GPa, respectively. The in-plane shear strength along the fiber direction is 35.8 MPa, while the corresponding shear modulus is measured to be 3.7 GPa. The epoxy resin has a tensile strength of 40.5 MPa, shear strength of 12.7 MPa, a modulus of elasticity of 3.4 GPa, its bond strength with concrete (cohesive failure) is 3.7 MPa and elongation is 2.3%.

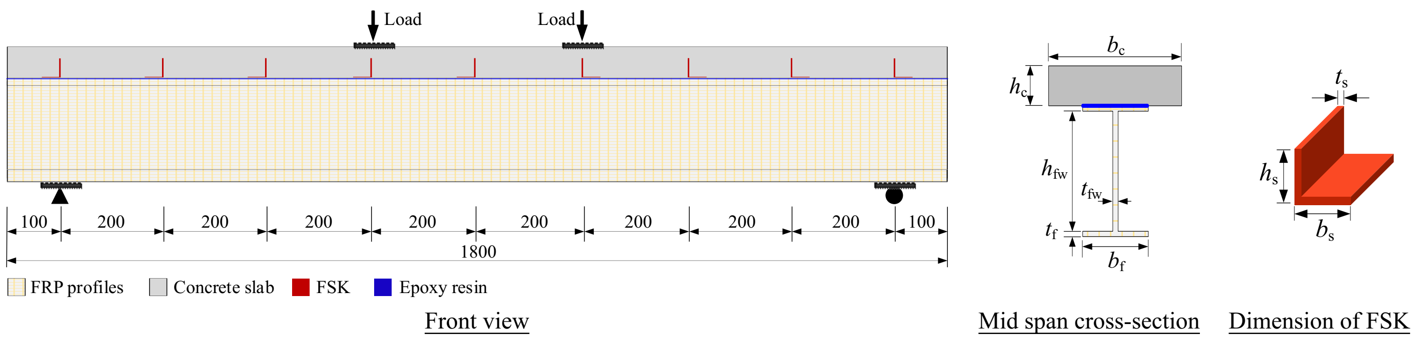


Fig. 1: Dimensions of FSK reinforced FRP-UHPC composite beam. (unit: mm).

3. Finite element model

3.1. Establishment of FE model

A refined FE model of FRP-UHPC composite beams with FSK was established using the commercial software ABAQUS, as shown in Fig. 2. The analysis considered the nonlinear effects caused by large displacements and employed standard (static, general) solvers. The solution technique employed was Full Newton method.

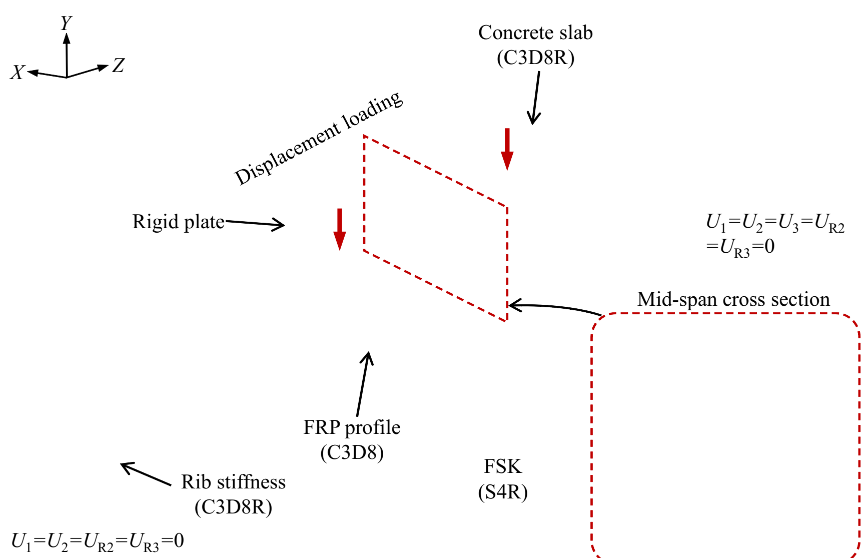


Fig. 2: FE model of FSK reinforced FRP-UHPC composite beam.

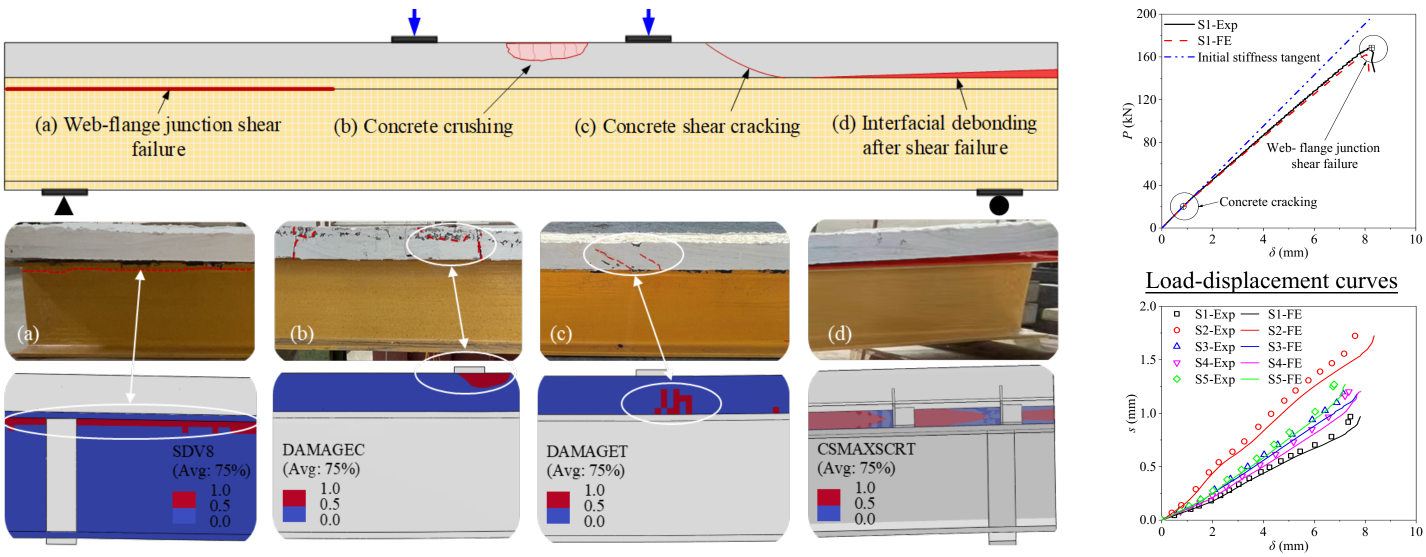
Interactions: A bilinear cohesive zone model (CZM) [8] was adopted to simulate the adhesive layer behaviour between concrete and FRP profiles, as well as between FSK and FRP profiles. Damage evolution at the interfaces was determined based on the maximum stress criterion [9]. "Embedded Region" approach was used to embed FSK within the concrete. Frictional contact was also employed between the vertical stiffeners and FRP profiles.

Element types and meshing: To enhance computational efficiency, concrete was modelled using solid elements C3D8R (8-node reduced integration elements) with a mesh size of 10 mm. To prevent shear locking phenomena in FRP profile elements, solid C3D8 elements (8-node fully integrated elements) were also employed for the FRP profiles, with the FRP flanges and web divided into 4 layers [10] along the thickness direction, each with a mesh size of 10 mm. FSK was modelled using standard shell elements S4R (4-node reduced integration elements) with a mesh size of 5 mm.

Material constitutive: The CDPM [11] was employed to simulate the stiffness degradation of concrete due to compression and tension-induced damage, with the tension and compression damage factors determined using the energy-based method [12]. FSK and FRP profiles demonstrate orthotropic characteristics. Here, engineering constants are employed to simulate their mechanical behaviour in three directions. Compared with the two-dimensional Hashin failure criterion [13] provided by ABAQUS, Puck failure criterion [14] can predict the fracture angle of FRP matrix more accurately and do better on shear failure prediction results. Thus, a three-dimensional UMAT subroutine based on the Puck failure criteria was developed and integrated into ABAQUS to accurately simulate the progressive failure behaviour and material response of FRP profiles.

3.2. Model verification

Figure 3 presents a comparison between experimental and numerical results of the failure modes. The concrete slab's cracking and crushing are characterized using the concrete compression damage factor (DAMAGEC) and tensile damage factor (DAMAGET) within the CDPM framework, respectively. The shear failure at the junction of the FRP web and flange is represented by the matrix damage factor (SDV8) obtained from the Puck criteria.



Failure modes Load-end slip curves

Fig. 3: FE model of FSK reinforced FRP-UHPC composite beam.

During the initial stage, cracking appeared at the mid-span of the concrete bottom in all specimens. As loading continued, the matrix at the end of FRP web and flange began to bulge, and the interlayer adhesive layers started to delaminate. With the load increase, shear failure occurred at the web and flange junction and extended into the loading point. The concrete slabs initially developed diagonal cracks at the shear span, extending from the shear span into the pure bending span. When matrix damage at the web and flange junction extended, the end web disconnected from the upper flange, resulting in instability and ultimate failure of the composite beams. Therefore, the failure of the FRP-UHPC composite beams is primarily characterized by shear failure.

The load-deflection curves of FRP-UHPC composite beam exhibits linearity before concrete cracks. After concrete cracking, the FRP-UHPC composite beams continue to exhibit linear behaviour until failure, while the shear stiffness gradually decreased.

Before concrete cracking, the end slip of the composite beams is minimal and exhibits a relatively gradual increase. However, after concrete cracking, the end slip approximately linearly increases with the increase of deflection. The end slip remains less than 2.0 mm, indicating that the combination interface using FSK and epoxy resin adhesive bonding exhibits excellent anti-slip performance.

In summary, the refined FE model can accurately predict the failure modes, shear capacity, deformation and end slip of FRP-UHPC composite beam reinforced with FSKs.

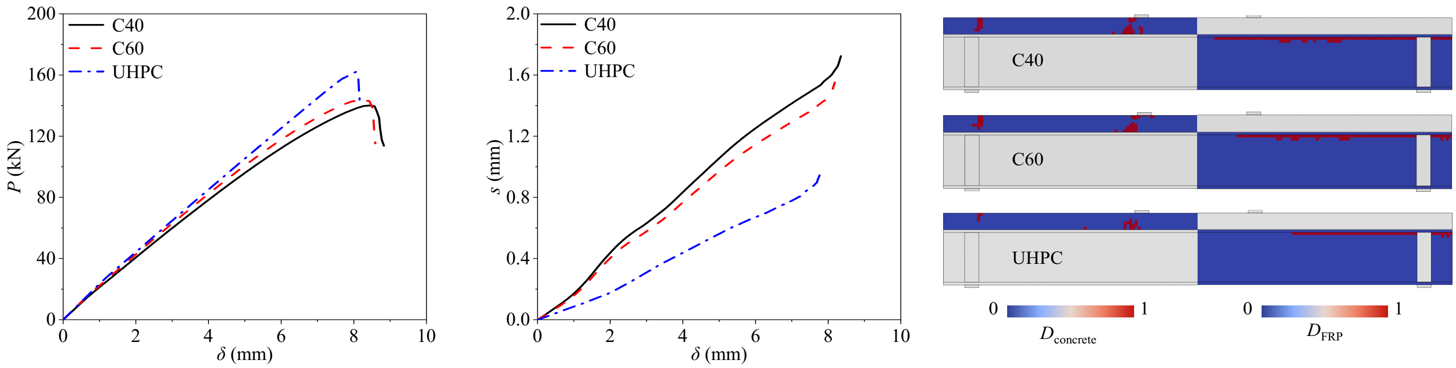
4. Parametric studies

4.1. Effect of concrete strength

Figure 4 illustrates the influence of concrete slab strength on the shear performance of FRP-UHPC composite beams. The cracking load of specimen with UHPC slab is improved by 100% and 61.9% compared to those of counterparts with normal strength concrete (NSC) slabs (C40 and C60), respectively. The ultimate loads are enhanced by 15.7% and 12.5%, respectively. This indicates that UHPC effectively inhibits concrete cracking and enhances the shear performance of the composite beams. Furthermore, FRP-UHPC composite beams exhibit the highest flexural stiffness, and their stiffness degradation rate is lower after concrete cracking. Thus, UHPC effectively enhances the stiffness of the composite beams and reduces the rate of stiffness degradation.

When the composite beams are subjected to the same deflection, the end-slip of FRP-UHPC composite beams is significantly smaller than that of FRP-NSC composite beams. As concrete strength increases, the end-slip gradually decreases, indicating a stronger flexural stiffness of composite beam and shear resistance of composite interface. According to the classical bond-slip theory of concrete and FRP, this is attributed to the superior crack resistance and higher tensile strength of UHPC compared to NSC, resulting in better bonding performance with FRP.

As concrete strength increases, the tensile damage area of concrete slab (i.e., the concrete cracking area) decreases, further confirming the crack-inhibiting effect of UHPC. Additionally, in FRP-UHPC composite beams, there is no occurrence of the compressive damage area in the concrete slab (i.e., the concrete crushing area). The failure mode of the composite beams transforms a synergistic bending-shear failure to a pure shear failure. Therefore, FRP-NSC composite beams exhibit pseudo-ductile characteristics, whereas FRP-UHPC composite beams undergo brittle failure.



Load-deflection curves | End slip-deflection curves | Failure modes

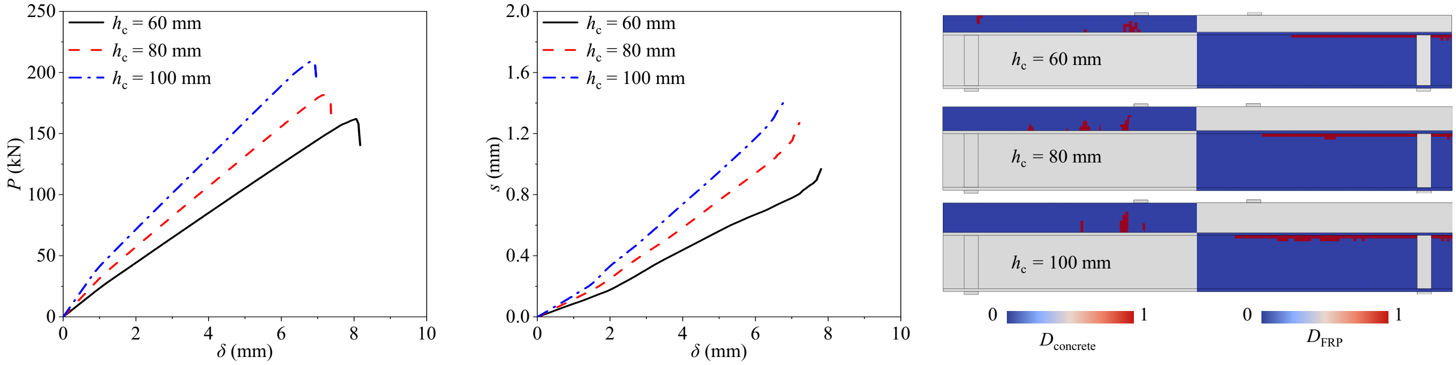
Fig. 4: Effect of concrete strength on shear behaviour.

4.2. Effect of concrete slab height

Figure 5 shows the influence of height of concrete slabs on shear performance of FRP-UHPC composite beams. With increasing the concrete slab height, the composite beam exhibits a significant improvement in cracking and ultimate load capacity, resulting in reduced deflection. This can be attributed to the increased section height, which effectively reduces the shear span to depth ratio, thereby enhancing the shear resistance of the composite beams. The flexural stiffness also increases with the increasing height of the concrete slab, but the rate of stiffness degradation accelerates. This is due to the increased height of the concrete slab, which accelerates the development of shear damage in the FRP profiles, leading to a significant increase in interfacial slip.

When the composite beams experienced the same deflection, the end-slip also increases with the height increase of concrete slabs. This phenomenon arises from the differing strains between FRP profiles and concrete slabs at the composite interface, coupled with the inherent deformation of FSK after loading, leading to inconsistent deformations at the composite interface. As the cross-sectional dimensions of concrete slabs increase, the strain difference at the composite interface between concrete and FRP becomes larger, resulting in greater differences in slip strains and additional curvature between concrete and FRP, thereby increasing the curvature and additional deflection.

When the composite beam reaches the ultimate load, the shear damage range of the FRP web and flange of the composite beam with the concrete height of 60 mm is smaller, while that of the concrete height of 100 mm is the largest. Thus, increasing the height of concrete slab exacerbates the development of shear damage in FRP profiles. Therefore, the excessive design of concrete slab height should be avoided in engineering design to prevent posing a significant threat to the structural safety of FRP-UHPC composite beams.



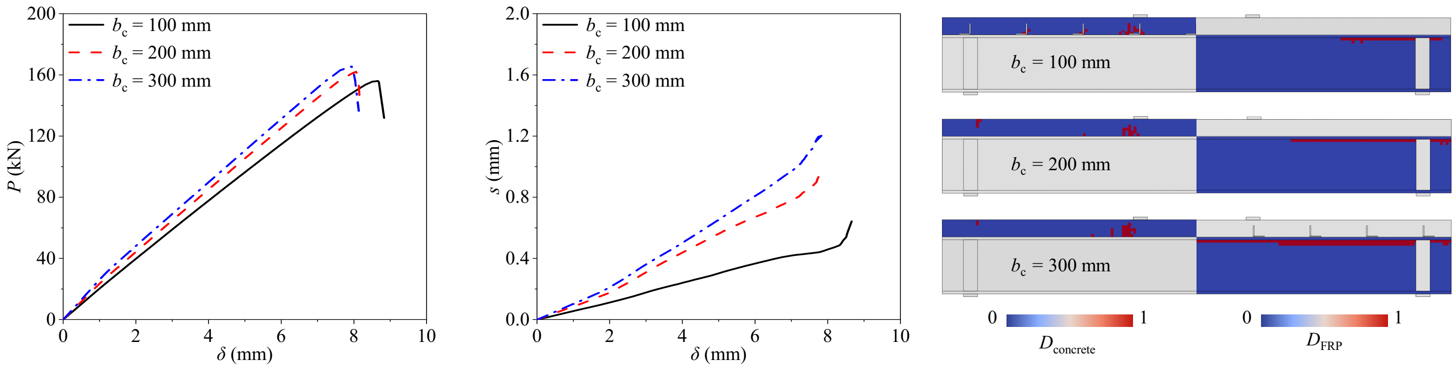
Load-deflection curves End slip-deflection curves Failure modes

Fig. 5: Effect of concrete slab height on shear behaviour.

4.3. Effect of concrete slab width

Figure 6 illustrates the influence of width of concrete slab on shear performance of FRP-UHPC composite beams. Increasing the width of the concrete slab has similar effects on the load-bearing capacity, deformation, slip behaviours, and failure modes of the composite beams as increasing the concrete height. Therefore, these effects are not reiterated here.

By combining Figs. 11 and 12, it can be observed that the ultimate load capacity of composite beams with a height of 100 mm is increased by 14.9% and 29.2%, respectively, compared to those with heights of 80 mm and 60 mm. In contrast, composite beams with a width of 300 mm exhibit only a 2.1% and 6.0% increase in ultimate load capacity compared to those with widths of 200 mm and 100 mm. This indicates that increasing the height of the concrete slab has a more significant impact on enhancing the flexural stiffness and load-bearing capacity of composite beams.



Load-deflection curves End slip-deflection curves Failure modes

Fig. 6: Effect of concrete slab width on shear behaviour.

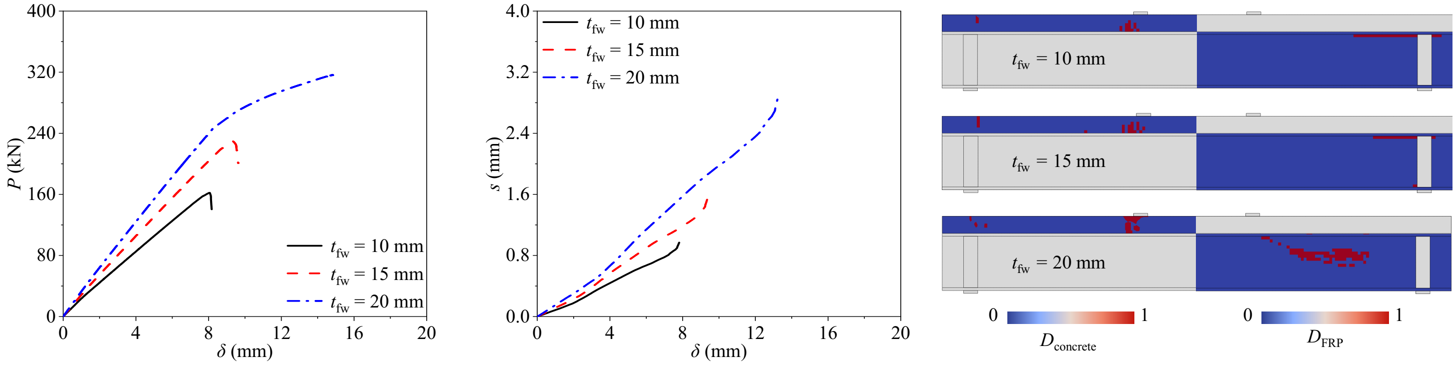
4.4. Effect of FRP web thickness

Figure 7 presents the influence of FRP web thickness on the shear performance of FRP-UHPC composite beams. With an increase in the FRP web thickness, the ultimate load of composite beams significantly increases. However, the cracking load of composite beams demonstrates only a minor increase. Under the same loading conditions, a thicker web results in lower shear stresses in the web, thereby, reducing the risk of shear failure. Additionally, the curvature at the mid-span section increases with the increasing of deflection, leading to an increase in the resultant moment in the compression and tension zones, consequently increasing the load-carrying capacity. The flexural stiffness of the composite beams also increases with the web thickness, and the rate of stiffness degradation notably decreases.

When composite beams experience the same deflection, those with a greater web thickness exhibit larger end slips. This phenomenon arises because as the thickness of the FRP profiles increases, the strain difference at the interface between concrete and FRP becomes greater. Consequently, there is a larger disparity in the slip strain and additional curvature between concrete and FRP, resulting in larger slip amounts and reduced capacity for cooperative deformation.

In composite beams with web thicknesses of 10 mm and 15 mm, the concrete slab does not experience crushing at ultimate load, but shear failure occurs at the connection between the web and flange of FRP sections. The composite beam with a web thickness of 20 mm exhibits the presence of a concrete crushing zone, while shear failure is observed as matrix damage at the web. Thus, the full utilization of the compressive performance of UHPC slab can be achieved by increasing the thickness of the

FRP web. Consequently, the failure mode of the composite beam shifts from shear to a combined flexural-shear coordinated failure, accompanied by a transition in failure characteristics from brittle to quasi-ductile.

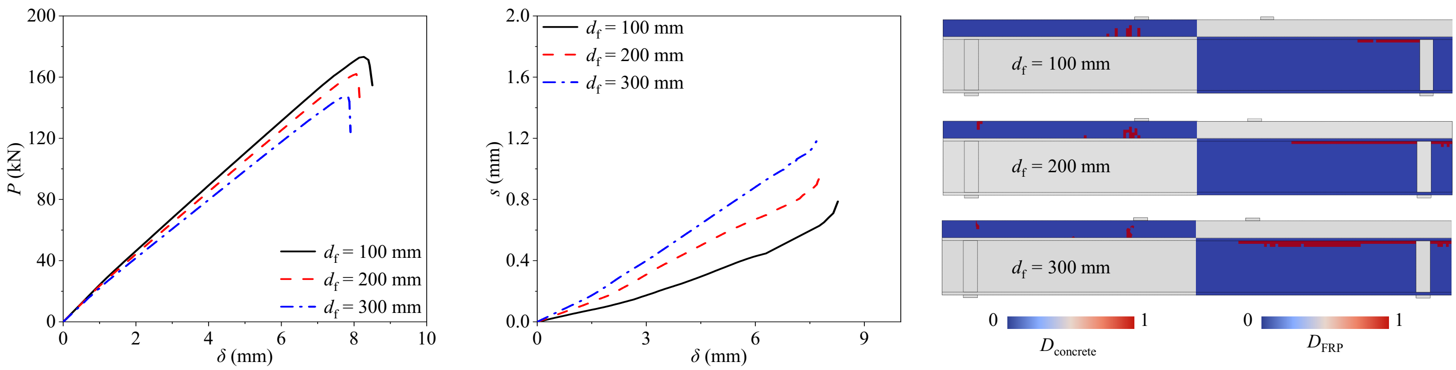


Load-deflection curves   End slip-deflection curves   Failure modes

Fig. 7: Effect of FRP web thickness on shear behaviour.

4.5. Effect of FSK spacing

Figure 8 depicts the influence of FSK spacing on the shear performance of FRP-UHPC composite beams. As observed in the figure, with a reduction in FSK spacing, the cracking load, ultimate load, and corresponding deflection of the composite beams, all, exhibit gradually improvements. This signifies that decreasing the FSK spacing effectively enhances the synergy between concrete and FRP profiles, consequently enhancing UHPC slab's contribution to the shear performance of the composite beams. Furthermore, as FSK spacing decreases, the stiffness of composite beams increases, but there is no significant difference in the stiffness degradation rate.



Load-deflection curves   End slip-deflection curves   Failure modes

Fig. 8: Effect of FSK spacing on shear behaviour.

5. Conclusion

In this paper, numerical simulation and comprehensive parametric analysis were carried out on FRP-UHPC composite beams with FSKs. The main conclusions are drawn as follows.

(1) FRP-UHPC composite beams fail in shear with brittle behaviour. Increasing the concrete strength enhances flexural stiffness and load capacity in composite beams but reduces deflection.

(2) Increasing the height and width of concrete slab improves the shear performance of composite beams, but it also leads to greater interface slip and subsequent shear damage at the FRP web.

(3) The flexural stiffness and load capacity of composite beams can be significantly improved by increasing the thickness of the FRP web. The failure mode also shifts from shear to flexural-shear coordinated failure.

(4) Reducing FSK spacing effectively enhances the load capacity, deformation, and flexural stiffness of composite beams while also improving shear performance at the composite interface and increasing UHPC's contribution to shear capacity.

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