Advanced Steel Construction – Vol. 17 No. 4 (2021) 394–402
DOI:10.18057/IJASC.2021.17.4.8

REVIEW OF VARIOUS SHEAR CONNECTORS IN COMPOSITE STRUCTURES

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A B S T R A C T

Shear connectors are devices that provide shear connection at the interface of steel girders and reinforced concrete slabs in composite structures to accomplish composite action in a flexure. The seismic response of composite structures can be controlled using properly designed shear connectors. This state-of-the-art review article presents considerable information about the distinct types of shear connectors employed in composite structures. Various types of shear connectors, their uniqueness and characteristics, testing methods and findings obtained during the last decade are reviewed. The literature, efficacy, and applicability of the different categories of shear connectors, for example, headed studs, perfobond ribs, fibre reinforced polymer perfobonds, channels, pipes, Hilti X-HVB, composite dowels, demountable bolted shear connectors, and shear connectors in composite column are thoroughly studied. The conclusions made provide a response to the flow of the use of shear connectors for their behaviours, strength, and stiffness to achieve composite action.

A R T I C L E H I S T O R Y

Received: 20 October 2020
Revised: 4 May 2021
Accepted: 5 May 2021

K E Y W O R D S

Anchors and anchorages;
Composite structures;
Shear connectors;
Push out test;
Concrete steel interface

1. Introduction

Composite structural systems have been used for decades and widely applied to bridges and building structures with a minimum utilisation of materials. The benefits of composite construction such as a rapid construction process, a reduction in vertical floor spaces, an overall decrease in self-weight, and low structure costs may help provide affordable services to a community. A steel beam–concrete slab with shear connectors is a well-known integrated structural element of composite structures (Fig. 1), which present economic feasibility and excellent structural performance. Shear connectors are used to combine two structural elements together at an interfacial stratum to avert the upright parting of a slab from a steel girder and provide a smooth transmission of longitudinal shear forces (Ahn et al.[1]). During an earthquake, horizontal inertial loads in a slab are distributed to a lateral load resisting frame with the provision of shear connectors at the connection face of the concrete deck and steel beam. The accoutrements of shear connectors could eradicate the slip of individual elements caused by horizontal inertia forces and thus the single T-beam mechanism achieved through composite action. Hence, the stiffness and strength of a composite element increase. The Indian standard code (BIS (Bureau of Indian Standards) IS 3935 1966[2]) specified Equation (1) for the shear force (Sh) at an interface plane, and these shear forces must be smoothly transferred through the shear connector in a composite structure.

$$S_h = \frac{V\, m_s}{I} \tag{1}$$

where V is the vertical load, ms represents the static moment, and I denotes the composite cross-section moment of inertia. Therefore, for the smooth transmission of the shear force among the concrete deck and steel girder, shear connectors should have adequate strength and stiffness.

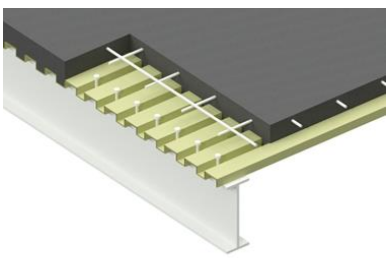

Fig. 1 Typical arrangement of a composite structure employing shear connectors

In this state-of-the-art-review paper, various configuration of shear connectors employed in composite structures in the last one decade and their uniqueness, characteristic, testing methods, and reported findings are reviewed. The efficacy and applicability of different shear connectors such as headed studs, perfobond, channels, pipes, Hilti X-HVB, fibre reinforced polymers (FRPs) connectors, composite dowels, demountable (bolted) connectors, and shear connectors in composite column are thoroughly studied. The use of shear connectors in rapports of their behaviours, stiffness, and strength to achieve composite action is discussed in detail.

2. Various shear connectors in composite structures

2.1. Headed stud shear connectors

Headed studs are the shear connectors commonly adopted in industries (Fig. 2); headed studs provide steel shank resisting longitudinal shear forces and have an anchorage head to prevent the vertical movement of slabs in composite structures (Ollgaard et al.[3]). Generally, to install a headed stud in the prefabricated steel girder beam, special welding equipment are essential. The weld strength should be higher than the stud strength. However, these welds generally face fatigue problems under repeated loadings (Lee et al.[4], Deng et al.[5], Liu et al.[6]). From the last seven decades, many studies have been performed on stud connectors after the invention of headed stud shear connector by Viest[7].

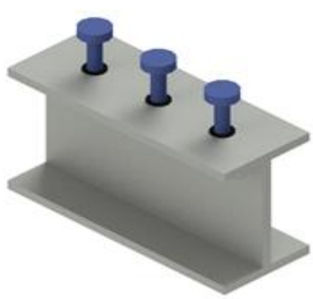

Fig. 2 Headed stud shear connector

Pallarés and Hajjar[8-9] proposed four formulas for the nominal shear strength of headed anchors in the solid slab when a composite beam imperilled the shear force responsible for concrete failure when it was subjected to static and cyclic loadings. Spremic et al.[10] experimentally investigated five different groups of four headed studs through push-out testing specified by Eurocode 4[11] to categorize the stiffness and shear strength performance between the group and standard arrangements. They aimed to minimise the space requirement of the stud in precast concrete slabs to lower than the

Eurocode 4[11] specified requirement of 5 times the stud diameter. Xu and Liu[12] established an analytical model to appraise the shear stiffness of rubber's sleeved headed studs per varying sleeve heights. Xu et al.[13] experimentally tested nine rubber's sleeved headed studs per varying sleeve heights to investigate fatigue performance and observed that with an increase in the rubber's sleeve height, the fatigue strength of the stud decreased. Ding et al.[14] experimentallu investigated the steel stud incased in foamed plastic block of Ethylene-Vinyl Acetate for the slip-released behavior under push out test. Further, the finite element (FE) simulation was performed on shear connector providing Polyvinyl Chloride protective shell layer for improvement in slip behavior of connector. Sjaarda et al.[15] presented a model to envisage the performance of composite beams by using the elastic properties and nonlinear load-slip curves of materials for a shear connector.

Sun et al.[16] explored the performance of the headed stud welded to composite deck accompanied by different steel profile decking receiving cyclic as well as monotonic loadings. The influence of the type, presence, and orientation of decking on the shear capacity of the welded headed stud was acquired experimentally. Mirza and Uy[17] observed the outcomes of headed stud connectors in composite structure with the effect of different strain regimes on concrete profiled steel sheeting and solid slabs using FE analysis, and concluded the significant influence of the strain regimes on strength prediction and load-slip behavior of shear connector in composite structure. Using the FE analysis, Qureshi et al.[18-19] considered the shear influence of central, favourable, and unfavourable positioning of single and double studs in a trough of profiled steel sheeting for experimental investigation. The efficacy of the thickness of profile sheets on the ductility, failure modes, and strength of the headed shear connectors employed in composite beams were determined throught numerical-experimental investigation. Qureshi et al.[18] explored the performance of shear connectors in composite beams under various spacings, stud layouts, and concrete strengths.

Table 1 presents the shear capacity equations of the headed stud connector in solid and profile steel sheeting concrete slabs conforming to international standards (ACI 2008[20], AISC 2005[21], EN 1994-1-1 2004[10], GB50017-2003[22], BSI (Bureau of Indian Standards) IS 3935-1966[2]); the equation developed in earlier historical studies, which led to the development of shear capacity equations for international standards (Viest[7], Slutter and Driscoll[23], Ollgaard et al.[3]); and latest studies (Pallarés and Hajjar[8], Qureshi et al.[19]).

Table 1
Shear-capacity equations of headed stud shear connector

Sr. No.	Reference	Headed stud in	Shear-capacity equations	Equation no.
1	EN 1994-1-1 2004[10]	Solid slab	$P = 0.29\alpha d^2\sqrt{E_c f_c'} \leq 0.8 A_s F_u$	2
			Here,	
			$\alpha = 0.2\left(\frac{h}{d}+1\right)$ $for\ 3 \leq h/d \leq 4$	
			$\alpha = 1$ $for\ h/d > 4$	
2	EN 1994-1-1 2004[10]	Profile deck	$P = 0.29 k_l \alpha d^2\sqrt{E_c f_c'}$ for parallel deck orientation	3
			$k_l = 0.6\frac{b_o}{h_h}\left(\frac{h}{h_h}-1\right) \leq 1$	
			$P = 0.29 k_t \alpha d^2\sqrt{E_c f_c'}$ for transverse deck orientation	4
			$k_t = \frac{0.7}{\sqrt{n_r}}\frac{b_o}{h_h}\left(\frac{h}{h_h}-1\right) \leq k_{t,max}$	
3	GB50017-2003[22]	Solid slab	$P = 0.43 A_s\sqrt{E_c f_c} \leq 0.7 A_s F_u$	5
4	GB50017-2003[22]	Profile deck	$P = 0.43 k_l A_s\sqrt{E_c f_c}$ for parallel deck orientation	6
			$k_l = 0.6\frac{b_o}{h_h}\left(\frac{h}{h_h}-1\right) \leq 1$	
			$P = 0.43 k_t A_s\sqrt{E_c f_c}$ for transverse deck orientation	7
			$k_t = \frac{0.85}{\sqrt{n_r}}\frac{b_o}{h_h}\left(\frac{h}{h_h}-1\right) \leq 1$	
5	AISC 2005[21]	Solid slab	$P = 0.5 A_s\sqrt{E_c f_c'} \leq A_s F_u$	8
6	AISC 2005[21]	Profile deck	$P = 0.5 A_s\sqrt{E_c f_c'} \leq R_g R_p A_s F_u$	9
7	ACI 2008[20]	Solid slab	$P_{Rd,S} = 0.65 A_s F_u$	10
			$P_{Rd,C} = k_{cp} k\sqrt{f_c'}(h)^{1.5}$	11
8	IS 3935-1966[2]	Solid slab	$P\ (kg) = 4.8\ h\ d\sqrt{f_c}\ For, h/d < 4.2$	12
			$P\ (kg) = 19.6\ d^2\sqrt{f_c}\ For, h/d \geq 4.2$	13
9	Viest[7]	Solid slab	$P = 5.25 d^2 f_c'\sqrt{\frac{4000}{f_c'}}\ when, d < 1$ inch	14
			$P = 5.25 d f_c'\sqrt{\frac{4000}{f_c'}}\ when, d > 1$ inch	15
10	Slutter and Driscoll[23]	Solid slab	$P = \frac{932 d^2\sqrt{f_c'}}{A_s}\ for\ Long\ Studs, h/d > 4.2$	16
			$P = \frac{222 hd\sqrt{f_c'}}{A_s}\ for\ Short\ Studs, h/d < 4.2$	17
11	Ollgaard et al.[3]	Solid slab	$P = 0.5 A_s\sqrt{E_c f_c'} < A_s F_u$	18
12	Pallarés and Hajjar[8]	-	$P_{vc} = 17 A_s {f_c'}^{0.45} {E_c}^{0.04}$	19
			$P_{vc} = 6.2 A_s {f_c'}^{0.2} {E_c}^{0.2}$	20
			$P_{vc} = 18 A_s {f_c'}^{0.5} h^{0.2}$	21
			$P_{vc} = 9\lambda {f_c'}^{0.5} d^{1.4} h^{0.6}$	22
13	Qureshi et al.[19]	Profile deck	$P_{U\ S\&D} = \alpha \times P_{F(0.9t_d)} \times (0.38 t_d + 0.66)$	23
				24
			$P_{CS} = \beta \times P_{F(0.9t_d)} \times (0.25 t_d + 0.78)$	25
			$P_{CD} = \beta \times P_{F(0.9t_d)} \times (0.16 t_d + 0.87)$	

2.2. Perfobond ribs shear connectors

Due to higher fatigue strength and easier installation than those of conventional headed studs, perfobond-ribbed (PBL) shear connectors were christened for composite structures (Leonhardt et al.[24], Oguejiofor and Hosain[25-27]). PBL connectors necessitate the use of perforated rectangular steel plates with circular holes that are more prominent than the diameter of transverse reinforcement and perforating rebars. PBL plates are conventionally welded at the top flange of steel girders.

Vellasco et al.[28] proposed T-rib perfobond shear connectors (Fig. 3a) that were useful in hogging moment areas, corner, and edge column flanges for composite portal frames to transfer forces from rebars. Vianna et al.[29] incorporated one or two rows of two (Fig. 3b) or four holes (Fig. 3c) in the web plate of T-rib perfobond shear connectors. Ahn et al.[1] presented a PBL shear connector suitable for the mixed girder arrangement comprising prestressed reinforced cement concrete (RCC) and steel girders. Shear capacity equations were proposed for single and twin PBL ribs, which accounted for the role of concrete end-bearing effects, the influence of concrete-dowel, and transverse reinforcements in rib holes. Vianna et al.[30] tested T-rib connectors with many variables such as high-grade concrete, connector holes with steel reinforcement, and slab thickness to evaluate the slip capacity, shear resistance, and failure mode. Costa-Neves et al.[31] emphasised the shear connector geometry and introduced double T-perfobond (Fig. 3d) and I-perfobond (Fig. 3e) connectors for composite girders. Their push-out test results revealed that the resistance enhancement of approximately 150%–300% is achievable due to the flange arrangement of connectors with and without transverse reinforcement in rib holes. Rodrigues and Laím[32] experimentally probed the performance of T-PBL, T shear connectors, and T-block in fire to find the shear resistance capacity, collapse mode, and ductility at ambient and different raised up temperatures.

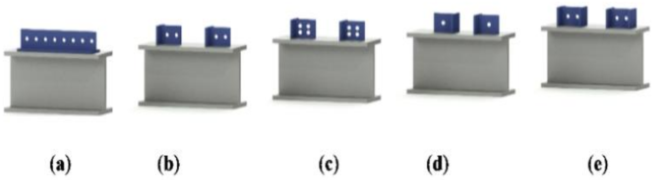

Fig. 3 Perfobond rib shear connectors: (a) T-ribs (Vellasco et al.[28]), (b) two holes in T-rib (Vianna et al.[29]), (c) four holes in two rows T-rib (Vianna et al.[29]), (d) 2T-Perfobond T-rib (Costa-Neves et al.[31]), and (e) I-Perfobond T-rib (Costa-Neves et al.[31])

Kim et al.[33] invented a "Y" shaped PBL shear connector (Fig. 4) and proved its superiority in fatigue and shear resistance through progressive experimental and analytical investigation under the static loading (Kim et al.[33-36]) and cyclic loading (Kim et al.[37-39]). Ramasamy and Govindan[40] studied the effects of triangular holes as perforation on PBL connectors to assess strength capacity through push-out testing. Two types of facing of triangular holes, facing flange TR1 (Fig. 5a) and facing opposite to flange TR2 (Fig. 5b), perfobond plates were discussed to discover the feasibility of resisting the shear capacity and slip. Zheng et al.[41] highlighted the importance of hole geometries in PBL shear connectors for shear capacity evaluation and investigated the performance of circular and long-hole PBL ribs through push-out testing. Fan and Zhou[42] proposed a new PBL connector, perfobond hoop (PBH), comprising PBL with stirrups embedded in the hole for steel–concrete composite arch elements, particularly for bridges. The experimental results showed the better mechanical property and higher shearing capacity of perfobond hoop than PBL connectors. The results of the theoretical and experimental studies of Zhang et al.[43-44] on PBL connectors in groups for the internal force transfer mechanism revealed the uneven distribution of forces in the elastic stage and even plastic deformation. Yu et al.[45] assessed the act of PBL connectors encased in recycled aggregate concrete slabs for strength appraisal of connection.

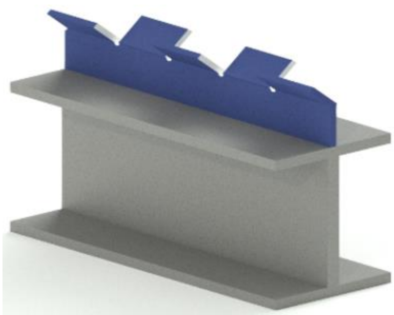

Fig. 4 Y-shaped perfobond rib shear connectors (Kim et al.[33])

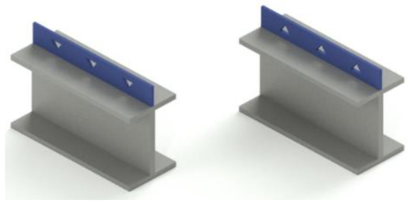

Fig. 5 (a) Triangular-apex fronting the flange and (b) triangular-apex conflicting to flange (Ramasamy and Govindan[40])

Su et al.[46] presented a new push-out testing system while assessing the behaviour of perfobond rib connectors to isolate the effect of friction and specimen size on structural performance by using PBL. Su et al.[47] investigated PBL in a composite girder bridge inlay with transverse rebar and concrete to evaluate the shear resistance capacity. Zhan et al.[48] experimented specific push-out tests (Fig. 6) on PBL and headed stud shear connectors in composite structures to see the stimulus of external pressure on the behaviour of shear connectors. The strength and stiffness of headed studs substantially improved due to the application of external pressure when the friction effect was employed.

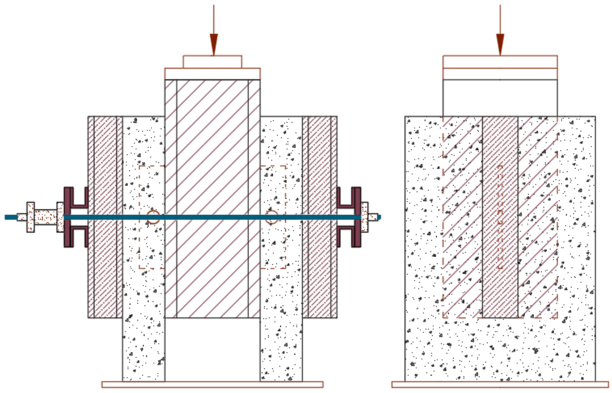

Fig. 6 External pressure on a test block for the push-out test (Zhan et al.[48])

2.3. FRP PBL shear connectors

FRP materials are utilised as shear connector support to enhance the flexural stiffness, obtain excellent corrosion resistance, and increase the capacity of structural strength. Zou et al.[49] used perforated FRP ribs as shear connectors to promote the mutual linking between a pultruded FRP I-girder and concrete slabs. Gwon et al.[50] performed the push-out test on the composite concrete-FRP module with FRP PBL connectors in the one-piece arrangement and introduced an equation to formulate the strength of FRP connectors in shear. Cho et al.[51] reported the importance of the number and diameter of rib holes for FRP PBL connector performance.

Table 2 presents the shear capacity equations developed by various researchers. Parameters responsible for strength predictions are highlighted with mark '✓'. Factors accountable for the PBL strength are: (a) concrete dowel action, (b) perforated rebars, (c) concrete slab end-bearing effects, (d) splitting resistance of concrete slabs, (e) transverse reinforcements, (f) chemical bonds, (g) empirical constants, and (h) other specific factors.

Table 2
Shear-capacity equations of PBL shear connector

Sr. no.	References	Shear-capacity equations	Shear capacity contribution factors								Equation no.
			a	b	c	d	e	f	g	h	
1	Oguejiofor and Hosain[26]	Q = $0.590A_{cc}\sqrt{f_c'} + 1.233A_{tr}f_y + 2.871nd_h^{\,2}\sqrt{f_c'}$	✓			✓	✓				26
2	Oguejiofor and Hosain[27]	Q = $4.5h_pt_pf_c' + 0.91A_{tr}f_y + 3.31nd_h^{\,2}\sqrt{f_c'}$	✓		✓		✓				27

3	Yoshitaka et al.[52]	Q = 3.38 $d_h{}^2\sqrt{t_p/d_h}\ f_c - 39.0$	✓						✓		28
		with 22.0< $d_h{}^2\sqrt{t_p/d_h}\ f_c$< 194.0	✓	✓					✓		29
		Q = 1.45 $\left[(d_h{}^2 - d_{rh}^2)\ f_c + d_{rh}^2 f_y\right] - 26.1$									
		with 51.0< $(d_h{}^2 - d_{rh}^2)\ f_c + d_{rh}^2 f_y$< 488.0									
4	Al-Darzi et al.[53]	Q_u =255.31+7.62 $\times 10^{-4} h_p t_p f_c' - 7.59 \times 10^{-10} A_{tr} f_y + 2.53 \times 10^{-3} A_{cd}\sqrt{f_c'}$	✓		✓		✓		✓		30
5	Ahn et al.[54]	Q = 3.14 $h_p\ t_p\ f_c + 1.21 A_{tr} f_y + 2.98 n d_h{}^2\sqrt{f_c}$ – Single Rib PBL	✓		✓		✓				31
		Q = 2.76 $h_p\ t_p\ f_c + 1.06 A_{tr} f_y + 2.61 n d_h{}^2\sqrt{f_c}$ – Twin Rib PBL	✓		✓		✓				32
6	Zhao and Liu[55] and Deng et al.[56]	Q = 1.38 $(d_h{}^2\text{-}d_{rh}^2)\ f_c + 1.24\ d_{rh}^2\ f_y$	✓	✓							33
7	Verissimo[57]	Q_u =4.04 $\frac{h_{sc}}{b} h_{sc} t_{sc} f_c' + 2.37 n D^2\sqrt{f_c'} + 0.16 A_{cc}\sqrt{f_c'} + 31.85 \times 10^6 \frac{A_{tr}}{A_{cc}}$	✓		✓	✓	✓				34
9	Medberry and Shahrooz[58]	Q_u =0.747b$h_{ecs}\sqrt{f_c'} + 0.413 b_f C_L + 0.9 A_{tr} f_y + 1.66 n\pi\left(\frac{d_h}{2}\right)^2\sqrt{f_c'}$	✓			✓	✓	✓			35
10	Deng et al.[56]	Q =0.5$A_s\sqrt{E_c f_c'}$ + 1.38 $(d_h{}^2 - d_{rh}^2)\ f_c + 1.24 d_{rh}^2 f_y$	✓	✓						✓	36
11	Gwon et al.[50]	Q_{FRP} =1.84$b_f C_L + 7.346 n\pi\sqrt{f_c'}\left(\frac{d_h}{2}\right)^2 + 0.95 A_{vf} f_r$	✓			✓	✓				37
12	Su et al.[47]	Q_u =$A_{cd}\tau_{cu} + A_{tr}\tau_{sy}$	✓				✓				38
		If,									
		$A_{tr}(\beta' A_{tr}\tau_{su} - \tau_{sy}) \leq A_{cd}\tau_{cu}$									
		Q_u =$\beta' A_{tr}\tau_{su}$									
		If,					✓				39
		$A_{tr}(\beta' A_{tr}\tau_{su} - \tau_{sy}) > A_{cd}\tau_{cu}$									
		Here, $\tau_{cu} = \alpha_c k_s\sqrt{f_c f_t}$									
13	Zheng et al.[41]	For circular hole PBL, Q_u =1.85$[(A - A_{tr})f_c + A_{tr} f_u] - 26.1 \times 10^3$	✓	✓							40
		For long-hole PBL, Q_u = 1.76 $(A - A_{tr})f_c + 1.58 A_{tr} f_y$	✓	✓							41
14	Zou et al.[49]	Shear failure in FRP plate, Q_u =1.1$A_{shear} S_{xy}$ Here, $A_{shear} = (L - 0.7 d_h n) t_p$								✓	42
		Failure in a concrete wedge, Q_u =4.5$h_p t_p f_c'$ + 3.31$n d_h{}^2\sqrt{f_c'} + 0.91 A_{tr} f_y$	✓	✓			✓				43

2.4. Composite dowels as shear connectors

Kopp et al.[59] presented the contextual data of puzzle shaped (PZ) and clothoidal (CL) composite dowels (Fig. 7) for their application as shear connectors in composite beam. The information have been utilised to derive technical rules to prepare the instructions for structural design principles, ultimate limit states, production, and construction. The bidirectional and even distribution of the shear force in composite structure could occur with the symmetric geometry of CL and PZ composite dowels (Seidl et al.[60]). The radius connections of these dowels provide favourable fatigue resistance and relevant strength to fatigue cracks. Hechler et al.[61] reported a fatigue design concept of PZ continuous shear connectors in prefabricated composite beam construction. Dudziński et al.[62] studied the fatigue cracks and fatigue durability of composite dowels through the beam test and FE analysis of the modified CL-shaped composite dowels. Lorenc et al.[63] revealed the behaviour of PZ (PZ 300/100) shear connectors for load-carrying capacity through shear resistance in full-scale push-out tests under static loadings. The influencing parameters such as the dowel size, web thickness, and grade of steel were studied during testing.

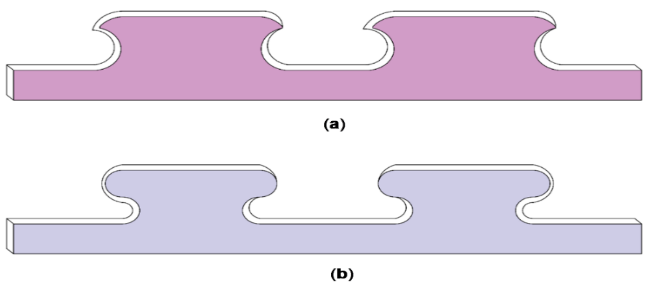

Fig. 7 (a) Clothoidal and (b) puzzle shape composite dowels used as shear connectors (Kopp et al.[59])

2.5. C-shaped angle and channel shear connectors

In general, the low strength of headed studs and complications regarding the provision of transverse rebar in PBL holes lead to the possibility of the development of C-type shear connectors. The two times higher shear strength of channel connectors than that of the headed stud and their better working environment for reinforcement than the working environment of PBL connectors were ascribed to their developed constructability advantages (Shariati et al.[64]). C-shaped connectors are available in two forms: angle and channel profile. Table 3 presents the standard equation used to predict the shear strength of channel connectors and some selective studies contributing in equation development are referenced.

Table 3
Shear-capacity equations of channel connector

Sr. no.	Reference	Shear-capacity equations	Equation no.
1	AISC 2005[21]	$P_c = 0.3(t_f + 0.5t_c)L_c\sqrt{f_c' E_c}$	44
2	NBC (National Research Council) 2005[65]	$P_c = 36.5(t_f + 0.5t_c)L_c\sqrt{f_c'}$	45
3	GB 50017-2003[22]	$P_c = 0.26(t_f + 0.5t_c)L_c\sqrt{f_c' E_c}$	46
4	BIS (Bureau of Indian Standards) IS 3935-1966[2]	$P_c\ (kg) = 10.7\ (h + 0.5t_c)L_c\sqrt{f_c}$	47
5	Soty and Shima[66]	$P_c = \text{kh}L_c\sqrt{f_c'}$ Here, $k = 63\ t_c/h\ + 1.60$	48
6	Pashan and Hosain[67]	$P_c = (336t_c^2 + 5.24L_cH)\sqrt{f_c'}$	49
7	Pashan and Hosain[67]	$P_{cm} = (1.7L_cH\dfrac{w_d}{h_d} + 275.4t_c^2)\sqrt{f_c'}$	50
8	Baran and Topkaya[68]	$P_c = \frac{2\times L_c\times t_c^2}{H} \times F_u + (f_c' \times 0.25 \times F_1 \times F_2 \times H)$	51
9	Tahmasbi et al.[69]	$P_c = 0.213\ L_c\sqrt{t}\sqrt{f_c'}$	52

Shariati et al.[70] experimentally studied the channel and angle shear (Fig. 8a and 8b) connectors entrenched in high strength concrete (HSC) to compare the performance of shear strength and ductility under static and cyclic push-out loadings. Channel connectors exhibit 6.8%–30.1% and 18.5% higher shear strength when exposed to static and full-reversed fatigue loadings, respectively, than angle connectors do in HSC. The performance of angel connectors was 7.5%–36.4% and 23.6%–49.2% lower for shear strength than that of channel connectors when employed in reinforced normal concrete subjected to monotonic and full-reversed cyclic loadings, respectively (Shariati et al.[71]). By taking the advantages of the properties of ultra-high performance concrete (UHPC) thin plates such as high tensile strength, satisfactory durability, and ultra-high compressive strength, Zhao et al.[72] proposed short steel channel connectors with thin UHPC plates for composite decks. Balasubramanian and Rajaram[73] reported the experimental findings of push-out static loading tests performed on composite structures with angle shear connectors. Deng et al.[5] proposed a unique channel connector type and compared its behaviour with T-rib and angle shear connectors in the experimental push-out test. The test results revealed that the maximum bearing capacity of the channel connector was approximately 92.1% and 47.5% superior than that of T-PBL connectors and angle connectors, respectively, with an adequate energy dissipation capacity. Titoum et al.[74] proposed an I-shaped connector and compared its behavior with the channel connector and confirms the similarity of their behaviors. So, the equation predicting the ultimate strength of channel connector as per Canadian code could significantly be adoptable for I-shape connector. Baran and Topkaya[68] found that the equation presented in Canadian and American specifications for predicting the strength of channel shear connectors was highly conservative as it considers limited parameters. Therefore, considering various lengths, the height of channel connectors, and the outcomes of 15 push-out tests, they invented a equation for determining the shear capacity of channel connectors. Pashan and Hosain[67] developed new equations to estimate the maximum shear capacity of channel connectors employing channel connectors on a composite beam interface with solid and wide-ribbed (ribs parallel to the beam) metal deck concrete slabs. Khorramian et al.[75] experimentally investigated the 112.5° and 135° tilted positions of angle shear connectors with the steel beam and various angle sizes and lengths for strength improvement. Shariati et al.[76] introduced soft computing artificial intelligence techniques and an adaptive neuro-fuzzy inference approach to forecast the behaviour of C-shaped tilt-angle connectors. Their findings open that the slip is a predominant factor and the inclination angle has secondary importance in the shear strength of tilted connectors. Soty and Shima[66] established an experimental beam-type test procedure and concluded that the effect of the shear force direction on shear connectors predominantly influences the strength of angle shear connectors. Shariati et al.[64] introduced V-shaped angle connectors (Fig. 8c) and investigated different parameters such as the height, length, and inclination angle of connectors with a flange of the I-steel beam for uplift resistance, high shear transfer, and ductility under monotonic and cyclic loadings. These results were compared with the C-types angle (Fig. 8b) and channel (Fig. 8a) connectors obtained in the investigation of Shariati et al.[70].

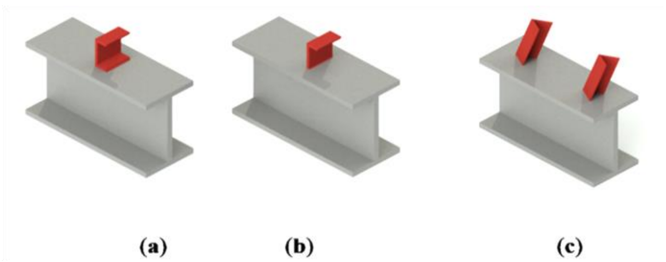

Fig. 8 (a) Channel shear connector, (b) angle shear connector, and (c) inclined V-shaped angle shear connector (Shariati et al. [64], [70])

Hicks et al.[77] evaluated the shear connectors in brides of the Canterbury and West Coast regions, and the Gisborne and Hawke's Bay regions for the New Zealand Heavy Engineering Research Association (HERA). They reported that 72% and 63% of bridges employed welded channels while 18% and 30% of bridges used V-angles as a shear connector in the Canterbury and West Coast regions (see Fig. 9), and the Gisborne and Hawke's Bay regions (see Fig. 10), respectively. In comparison, shear stud and other connectors have been used in 3% and 7% of bridges, respectively. The worked example of the Waipoua river composite bridge in New Zealand has also been specified for new design guidelines.

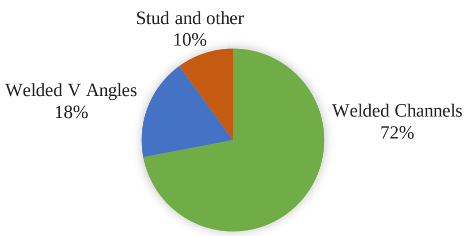

Fig. 9 Different forms of shear connector employed for the Canterbury and West Coast region composite bridges (Hicks et al.[77])

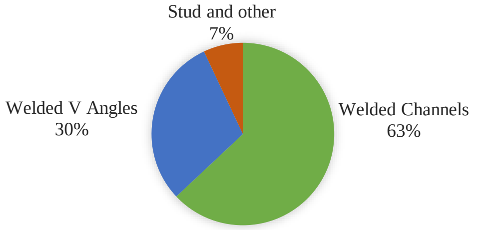

Fig. 10 Different forms of shear connector employed for the Gisborne and Hawke's Bay region composite bridges (Hicks et al.[77])

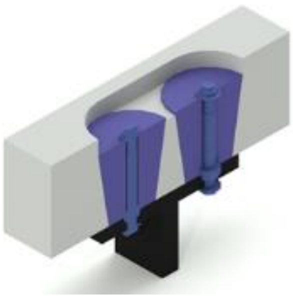

Fig. 12 Cut section of locking nut shear connector (Suwaed and Karavasilis[87])

2.6. Demountable bolted shear connectors

To form steel-concrete composite structures, demountable and bolted connections should be substituted with the frequently employed welded-headed studs. To potentially reuse structural elements including steel beams from composite structures after any destruction, demountable shear connectors are a suitable means for dismantling the structural beam element from the concrete slab. Various novel demountable bolted connectors and corresponding studies are presented here.

Pavlović et al.[78] studied the behaviour of four identical specimens of M16 grade 8.8 high strength single embedded nut bolt shear connectors in the solid slab and headed shear stud connectors by conducting the standard push-out test according to the Eurocode 4[10] specifications. G8.8 high strength single embedded nut-bolt shear connectors achieved 95% higher strength in shear resistance and 50% higher stiffness than the welded headed stud shear connectors did. Dai et al.[79] conducted several experimental static shear tests on solid slabs with demountable shear connectors having different collar sizes manufactured using standard headed stud shear connectors. Demountable connectors were be more ductile than welded connectors with high initial stiffness, but both exhibited a similar ultimate capacity (Dai et al.[80]). Yang et al.[81] proposed a new demountable connector comprising a long bolt, a short bolt, and a coupler and discovered its shear failure performance in composite action from the results of push-out tests. Rehman et al.[82] embarked demountable connectors having the similar shear strength as welded shear studs have on a concrete slab with profiled metal decking. Moreover, they satisfied the Eurocode 4 standard ductility criteria of 6 mm. Using the FE analysis, Patel et al.[83] evaluated the significance of shear connectors in a steel beam with profiled decks slab, and hollow core concrete slab composite structures.

Kozma et al.[84] developed and analysed different bolted demountable shear connection systems for repeated use in solid composite slabs with and without profile steel sheeting. The systems included cylindrical, coupled, and coupled epoxy bolted connections with L-profile (Fig. 11). The failure mode was shear failure but it occurred in a brittle critical manner. Kwon et al.[85] suggested the use of three different post-installed shear connectors as a high-tension friction-grip bolt, a double-nut bolt, and an adhesive anchor to enhance the strength of existing non-composite bridge girders. Sjaarda et al.[86] explored the behaviour of embedded bolt shear connectors by testing large-scale composite beam specimens. Suwaed and Karavasilis[87] proposed an assembly of novel high-strength bolted demountable shear connectors (Fig. 12), called locking nut shear connectors (LNSCs) that comprised special locking nuts to prevent slipping in holes for precast composite bridges.

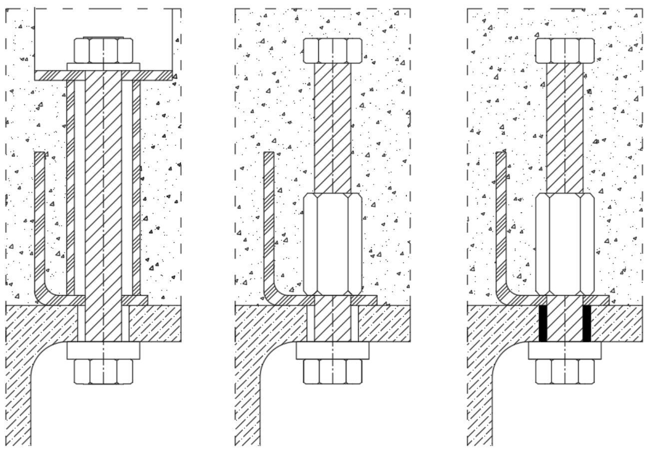

Fig. 11 Bolted demountable shear connections: (a) cylindrical system, (b) coupler system with pretensioned bolt, and (c) coupler system with injection bolts (Kozma et al.[84])

2.7. Blind bolt shear connectors

To develop highly advantageous and workable demountable shear connection systems that are easy to install, Mirza et al.[88] adopted two removable blind bolts, BB1 and BB2, as a shear connector in a composite structure for slip performance assessment. Pathirana et al.[89] and Henderson et al.[90-91] utilised the same blind bolts to evaluate flexural behaviour and to determine the dynamic behaviour of composite beams by conducting a full-scaled beam test, respectively. Ban et al.[92] reported a long-term effect of static loadings (as a time-dependent behaviour) on composite steel–concrete beams utilising demountable blind bolting shear connections through experimental and FE analyses. Almost all researchers have concluded that the performance of blind bolt shear connectors for strength and stiffness is highly tantamount to that of the welded headed studs; however, the blind bolts presented brittle failure nature.

2.8. Pipe shear connectors

Nasrollahi et al.[93] used pipes as shear connectors having vertical and horizontal positioning in composite steel beams and revealed the economical use of pipes as shear connectors in the moderate shear strength requirement range of 150–350 kN.

2.9. Hilti X-HVB shear connectors

The Hilti X-HVB shear connector is an innovative shear connector that has L-shape and can be fastened with two nails to a beam (Fig. 13). Powder-actuated tools are required to fasten X-HVB to steel beams through two nails. X-HVB shear connectors prevent vertical uplift forces by using the X-HVB head and nails and are designed to resist desired shear forces with suitable ductility (Hilti X-HVB System[94]). Gluhović et al.[95] tested the prefabricated composite deck by conducting push-out tests pursuant to Eurocode 4[10] to assess the shear capacity of X-HVB connectors with powder-actuated fastener X-ENP-21 HVB nails. Their results showed that 26% higher slip to failure and 16% higher ultimate shear resistance to forward orientated shear connectors.

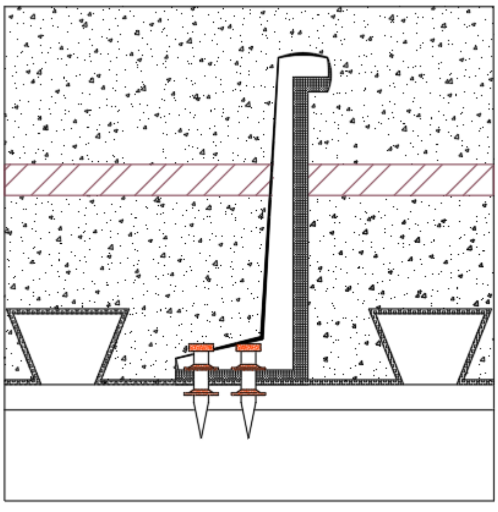

Fig. 13 Hilti X-HVB shear connector (Hilti X-HVB System [94])

2.10. Combination of different shear connectors

The advantages of headed stud shear and PBL connectors together have enabled researchers to improve the shear behaviour of composite structures. Deng et al.[56] developed and tested a combination of headed shear connectors with a single perfobond rib (Fig. 14) by using ten push-out test specimens for evaluating the fracture mode, shear capacity, load-slip behaviour, and ductility. Gu et al.[96] established a combination-type perfobond rib shear connector having a pre-embedded tube, pre-embedded sleeves, and shear pockets in concrete for shear performance assessment.

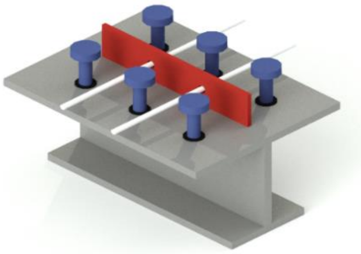

Fig. 14 Combination of headed shear connectors with a single perfobond rib (Deng et al.[56])

2.11. Shear connectors in composite Column

Composite columns are the structural member of composite structure utilizing the properties of structural steel element and concrete together for enriching the structural behavior in compression. The application of shear connectors in a composite column enhances the performance of column and/or beam-column connection in shear resistance, axial strength, and ductility. Eghbali and Mirghaderi[97] utilized a vertical plate called through plate with rigid shear connectors (Fig. 15) in beam-column connection for the composite framed structure to constraint sliding among the steel beam and reinforced concrete column. The ¾ scaled experimental evaluation characterized the composite connection utilizing a through plate with rigid shear connectors as a fully restrained strong panel elastic nature. Whereas, Aguiar et al.[98] utilized Crestbond shear connectors (steel plate with regular cuttings similar to puzzle shape composite dowels used as shear connector shown in Fig. 7 (b)) in concrete filled-steel tube columns at the beam-column interface for shear load transfer.

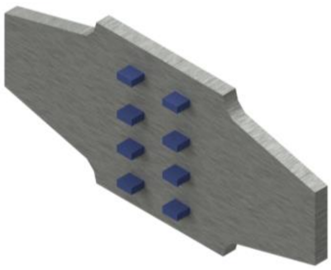

Fig. 15 Through plate with rigid shear connectors (Eghbali and Mirghaderi[97])

Odenbreit et al.[99] developed longitudinal, angled V-shaped and transversal flat shear connector for a steel-concrete composite column to overcome the difficulty of placing and handling the reinforcement associated with utilization of typical headed studs in the composite column. These three connectors were fabricated from conventional reinforcing bars and welded to the steel plates of a composite column under profiled positioning. Quio et al.[100] recommended using the steel plates as a shear connector welded to the square concrete-filled steel tube column. Alenezi et al.[101] used shear connectors for enhancement of compressive strength of cold-formed steel ferro-cement jacketed composite column. Three connectors, namely self-drilling screw, bar angle bolts, and normal bolt shear connectors in composite column-lipped C-channel, were evaluated for load-slip analysis through eight push-out test experiments. Younes et al.[102] employed high strength bolts as a shear connector in concrete-filled thin-walled steel tube short column (Fig. 16) for axial strength improvement. Ductility, buckling, and axial capacity of the composite column due to shear connectors performance were investigated through ten experimentally tested specimens. Whereas, from load-displacement analysis of experimental push-out test, Neto and Sarmanho[103] marked the judgement that bolts application in the composite column as a shear connector exhibits ductile and flexible nature. Tian et al.[104] proposed a shear connector utilizing advantages of engineering cementitious concrete together with perforated steel plate connectors and perforated steel reinforcement for composite column. Eight short columns were tested experimentally under push-out test, and results demonstrated the attribute of ductile failure.

Fig. 16 High strength bolts as a shear connector in concrete-filled thin-walled steel tube short column (Younes et al.[102])

3. Conclusions

Shear connectors are used to join steel girders/beams and RCC decks/slabs together in composite structures for bridges and building. The commonly adopted connectors in industries are welded headed studs, PBL connectors, angle and channel connectors, and demountable bolted connectors. The push-out test is the most commonly adopted typical testing method used to assess the performance of connectors for shear capacity and is performed according to the Eurocode 4 specifications. However, the push-out test omits the information valuable for accounting the interfacial friction, bending, and distribution of forces among connectors. Therefore, researchers have adopted another method called beam test with or without the push-out test for exploring the overall significance of shear connectors in composite structures. The beam test revealed higher yielded values because it accounted for the friction and redistribution of forces among connectors (Ollgaard et al.[3]). In this conclusion section, the adaptability, efficacy, and uniqueness of various shear connectors are discussed.

3.1. Headed stud shear connectors

The welded headed stud shear connectors are surfeited in studies and widely adopted in composite solid concrete slab construction. However, its utilisation in precast composite concrete slabs remains a topic that requires further investigation. The utilisation of rubber sleeves in studs presents potential to overcome the problem associated with fatigue resistance and requires further investigation. Moreover, the application of the headed studs welded through steel profile decks, in which weld flaws could be harmful for ductility and strength and thus lead to additional welding requirements, is a study area. The dominance of the sheet obese and proper positioning of studs in the trough of profile sheeting is a factor contributing to composite shear action.

3.2. PBL shear connectors

PBL connectors are popular in the scientific community due to their superior performance to the performance of headed studs for fatigue and strength contribution in composite structures. Researchers have reported T-rib PBL with various geometrical shapes and hole arrangements and have discovered the shear capacity contribution of concrete dowel performance and the significance of transverse rebar in rib holes.

3.3. FRP PBL shear connectors

FRP-rib connectors are reported to exhibit excellent strength and stiffness in composite action; however, their studies are restricted to a precast one-piece arrangement and in situ situations remain to be performed.

3.4. Composite dowels as shear connectors

CL and PZ dowels are robust shear connectors in composite structures, specifically in pre-fabricated composite bridges. Composite dowels have higher shear strength and functional deformation capacity than headed studs even in high-grade concrete. However, missing standards for the application of composite dowels as shear connectors has led to misunderstanding in structural design principles and production.

3.5. C-shaped angle and channel shear connectors

The shear performance of angel connectors was lower than that of channel connectors when employed in reinforced normal concrete under monotonic and cyclic loadings (Shariati et al.[71]). The function of channel connectors for bearing capacity was supreme than that of T-rib connectors. Due to the better uplift counteraction and ductility fulfilment of V-shaped angle connectors than that of conventional channels and angle connectors, they are recommended to be used for future industrial applications.

3.6. Demountable bolted shear connectors

The drawbacks of using the welded studs in composite construction are overcome by using demountable bolted shear connectors for fatigue performance, dismantling parent elements in rapid non-destructive deconstruction, and employing in precast construction. Providing innovative LNSC facilitates rapid work and minimises construction tolerance problems such as disassembly or replacement and repair of steel and precast elements in bridge structures.

3.7. Different shear connectors

The behaviour of blind-bolted shear connectors for strength as well as stiffness is considerably alike to that of the welded headed stud; however, the blind bolts exhibit a brittle failure nature. Vertical pipes are suitable to be used as shear connectors under moderate shear strength requirements. Hilti X-HVB does not require welding or electric power for installation; thus, it does not infringe spot warm works as welded headed studs, that is, fire watch, and regulations, do.

3.8. Shear connectors in composite column

The utilization of through plate with rigid shear connectors in beam-column connection characterized the performance as a fully restrained strong panel elastic nature. Crestbond shear connectors significantly transfer the shear load at a connection in the concrete-filled steel tube columns. Shear connectors fabricated from conventional reinforcing bars and welded to the steel plates of a composite column under profiled positioning are advantages to overcome the difficulty of placing and handling reinforcement associated with the utilization of typical head studs in composite columns. The high strength bolts as a shear connector enhance the axial strength performance and exhibit ductile and flexible nature in the concrete-filled thin-walled steel tube short column.

Acknowledgement

The authors are indebted for the support they have received by Sardar Vallabhbhai National Institute of Technology, Surat, under the Ministry of Education (MoE), India.

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