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STATIC STRENGTH OF THE SHEAR CONNECTORS IN STEEL-CONCRETE COMPOSITE BEAMS - REGULATIONS AND RESEARCH ANALYSIS -

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Abstract. *The paper reviews the most important analytic expressions, on the basis of the developed industrial countries' contemporary literature, for determination of strength of shear connectors in steel-concrete composite beams. The mechanism of possible failure and basic criteria used for defining of the shear connector strength at composite slabs and composite slabs with profiled sheet. Special analysis has been done in the expressions and recommendations given by Eurocode 4 in the area of shear connector strength, both elastic and rigid. For all the presented regulations, a comparative analysis with our standing standard (JUS) addressing this area is given. Along with the comparative review of the regulations, a commentary on the strength of the shear connectors in composite beams is given.*

1. GENERAL

Shear connectors, anchors (hoop, loops, struts) are used as a means for composing steel and concrete, as well as friction through high value crews and their combination.

There is a common term - shear connectors that defines the various forms of steel structure parts connected to the upper segment of the steel beam most often by welding or pre-the stressed screws.

2. FORMING OF THE SHEAR CONNECTORS

The transmission of shear forces and the intensity of stress in the steel beam, the weld that connects the shear connector to the flange of the beam, material of connector itself and the surrounding concrete of the slab, which all determines the strength, are highly dependant on the form of the shear connector. There are very different forms of means for composition that are used in practice.

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There are many types of shear connectors and they are most generally divided into **rigid and flexible,** according to the distribution of shear forces and functional dependency between strength and deformations (Fig. 1).

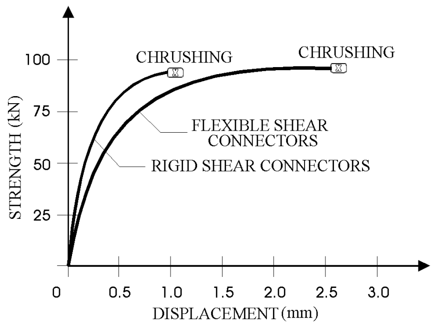

Fig. 1. Functional dependency between strength and displacement.

The rigid shear connectors resist shear forces through the front side by shearing, and they have insignificant deformations in the proximity of ultimate strength. They produce stronger concentrated stress in the surrounding concrete that results either in failure of concrete or in failure of weld.

Flexible shear connectors resist shear forces by bending, tension or shearing in the root, at the connection point of steel beam, where they are subject to plastic deformations when they reach the ultimate strength values. The manner of failure of flexible shear connector is more ductile and is not prompt. They maintain the shearing strength even with a lot of movement between the concrete slab and the steel beam.

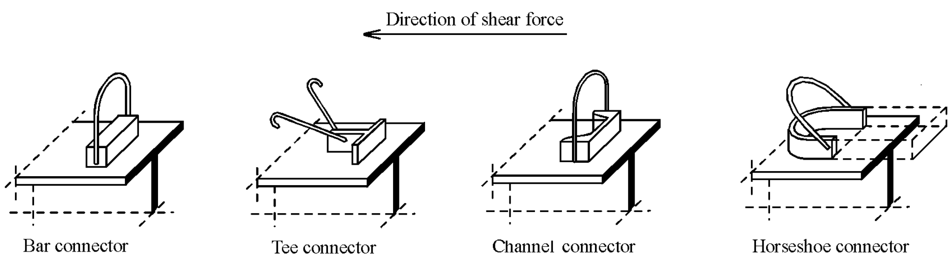

Fig. 2. Rigid shear connectors (with hoops)

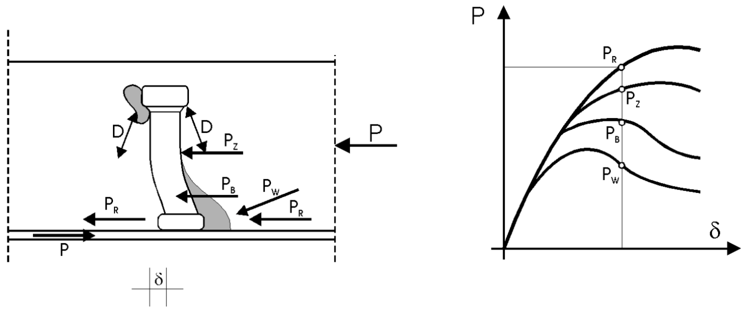

Fig. 3. The shearing forces distribution mechanism at stud shear connectors in a composite beam

At composite beam with slab (Fig. 3) the shearing force P is entered through the base of the shear connector into the concrete layer. The force marked as P_w is introduced at a small angle on the weld that connects the shear connector and the flange. With the increase of pressure in concrete, at the base of the shear connector, the concrete crushing occurs and the shear forces is transferred to the shank of the shear connector (force P_B). This causes the plastic deformations resulting from the bending of the shank of the shear connector, and it also causes the occurrence of tensile forces in the shear connector, which prevents vertical lift. Due to the tensile forces in the shear connector the pressure stress occurs in concrete, especially in the proximity of the shear connector head, which in addition, activates the friction forces at the contact between the concrete and the upper flange of the steel beams (force P_B). Horizontal component of the tensile marked with P_z is transferred to the shank of the shear connectors. The shear connector, in this case, fails immediately above the weld due to the action of tensile and shearing forces [3].

In the field of real stress states, that is exploitation load, the slim and rigid shear connectors act similarly, because they have an insignificant deformation that allows for the supposition that there is no moving between the concrete and the steel part of the cross-section. Because of these reasons, there is no difference in the calculation of strength in the elastic area, regardless of the type of shear connectors applied (rigid or elastic), because the cross section may be considered homogenous. However, for the calculation of the limit strength by the plasticity theory, the slim shear connectors have the advantage, because they allow, due to their plastic deformation, for the certain sliding between the concrete and steel, and thus, for the more favorable distribution of shearing forces. Their behavior is similar to the behavior of the basic material (steel beams) in the area of the failure.

3. STRENGTH OF THE SHEAR CONNECTORS

When calculating the composing means, apart from determining the shearing force V, it is necessary to know the strength of the individual, adopted, composing means – shearing connectors.

The calculation consists of either calculation of shearing force V which should be received by the shearing connector at a set distance, or in determination of the distance when the strength of one shearing connector is known, individually or in combination with an anchor.

When the strength of shear connectors is being determined, the Eurocode 4 defines: Characteristic strength $P_{Rk,}$ under which not more than 5% of the results can be expected, and designed strength P_{Rd} which is obtained by dividing the characteristic strength by the corresponding partial safety coefficient γ_V.

The main depending factors defining the strength of shear connectors are: shape and dimensions of the shear connectors, quality of its material, concrete strength, type of load (static and dynamic), way of connecting the steel beams, distance between the shear connectors, dimensions of the concrete slab, percentage and way of reinforcing. All these factors individually, and jointly, create a condition that the satisfactorily precise expressions for defining the strength can be reached only by the experimental research on the models for each individual shear connector shape.

The values for the maximum pressure stress in concrete σ_{max} obtained through examination, were 3,2 times greater than the concrete strength β_b. This indicates that it is the local pressure on concrete in question, whose transverse deformations are prevented, consequently significantly increasing concrete strength. Namely, it is about the three-axis load state of concrete in front of the shear connectors, which is between them.

The regulations of well-developed countries have, on the basis of these and many other latter research, given different values in terms of permissible increase of local concrete pressure in respect to the permissible increase of the pressure load for the certain brands of concrete.

3.1. Comparative review of the regulations for the rigid shear connector's strength

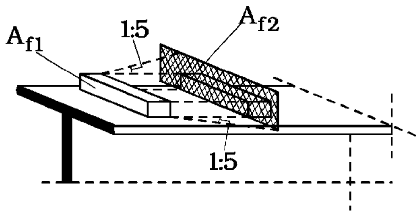

Fig. 4. Influence of the local pressure on the rigid shear connector's strength

Review of the regulations on the rigid shear connector's strength

Regulation	Strength	Stress increase
JUS of 1970	$N_{dop} = \sigma_1 \cdot A_{f_1} + S_a$	$\sigma_1 = \sigma \cdot \sqrt[3]{\frac{A_{f_2}}{A_{f_1}}}$
SIA 161	testing	testing
DIN of 1981	$R_d = A_1 \cdot \beta_{Rd} \cdot \sqrt{\frac{A_2}{A_1}}$	$\sigma = \beta_{Rd} \cdot \sqrt{\frac{A_2}{A_1}} \leq 1{,}6 \cdot \beta_{b28}$
BS 5400	$R_d = A_1 \cdot \beta_{Rd} \cdot \sqrt{\frac{A_2}{A_1}}$	$\sigma = \beta_{Rd} \cdot \sqrt{\frac{A_2}{A_1}} \leq 1{,}6 \cdot \beta_{b28}$
EC 4 of 1985	$R_d = A_1 \cdot \beta_{Rb} \cdot \sqrt{\frac{A_2}{A_1}} \cdot \frac{1}{\gamma_{mb}}$	$\beta_{Rb} \cdot \sqrt{\frac{A_2}{A_1}} \leq 2{,}5 \cdot \beta_{Rb}$
EC 4 of 1992	$P_{Rd} = \eta \cdot A_{f1} \cdot f_{ck} \cdot 1/\gamma_c$	$\eta = \sqrt{\frac{A_{f1}}{A_{f2}}} \leq 2{,}5$
JUS U. Z1. 010	$R_d = A_1 \cdot \eta \cdot \beta_{Rb}$	$\eta = \sqrt{\frac{A_2}{A_1}} \leq 3$

3.2. Comparative review of the regulations for the flexible shear connector's strength

Strength of the stud shear connectors in a composite beam

In calculation of the composite constructions by the limit state concept, and especially in application of plasticity theory, in cases where it is possible, in determination of the strength limit states, the slim (elastic) shear connectors have the absolute advantage. The most widespread, because of its economic aspect, resulting from the welding time (10-15 s) and uniformity of seam quality, is certainly **headed stud.**

The failure model created due to the concrete failure is shown in figure 5. Also, the distribution of longitudinal shearing forces (acting on the shear connector height) can be perceived here, as well as the most loaded zones in the surrounding concrete. It is prominent that the most loaded zones are at the food of the shank and in the proximity of the shear connector head.

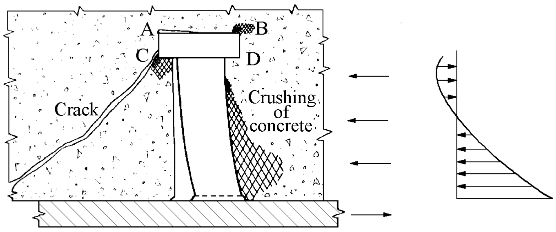

Fig. 5. Failure model at headed stud

Strength of the headed stud (Fig. 5), at the plasticity theory calculation, depends on two criteria: 1) Local concrete pressure and 2) shearing by the shear connector cross-section.

$$P_{Rd} = k_1 \cdot d^2 \cdot \sqrt{E_{cm} \cdot f_{ck}} \le k_2 \cdot f_u \cdot \frac{\pi \cdot d^2}{4} \qquad (1)$$

The first equation gives the strength at low quality of concrete and in that case the strength of the shear connector is the function of the square of the diameter of shear connector shank and the tensile strength of the shear connector's shank f_u. The coefficients k_1 and k_2 are there to establish the relation between the calculation models and average experimental results.

Review of the regulations on the stud connector's strength

Regulations	Strength dictated by the local concrete pressure	Strength dictated by the shearing along the cross-section of the shear connector
SIA 161	$R_d = 0{,}25 \cdot d^2 \sqrt{E_b \cdot \beta_{b28}}$	$R_d = 0{,}7 \cdot \frac{\pi \cdot d^2}{4} \cdot \sigma_u$
DIN	$R_d = \alpha \cdot 0{,}25 \cdot d^2 \cdot \sqrt{\beta_{wk} \cdot E_b}$	$R_d \le 0{,}7 \cdot (\frac{\pi \cdot d^2}{4}) \cdot \beta_s$
BS 5400	$R_d = 0{,}8 \cdot \frac{P_u}{1{,}1} = 0{,}73 \cdot P_u$	testing
EC 4 of 1985.	$R_d = 0{,}36 \cdot \alpha \cdot d^2 \cdot \sqrt{\beta_{bk} \cdot E_b} \cdot \frac{1}{\gamma_{mb}}$	$R_d = 0{,}7 \cdot \frac{\pi \cdot d^2}{4} \cdot \sigma_u \cdot \frac{1}{\gamma_{m\sim}}$
EC 4 of 1992.	$P_{Rd} = 0{,}29 \cdot \alpha \cdot d^2 \cdot \sqrt{f_{ck} \cdot E_{cm}} \cdot \frac{1}{\gamma_v}$	$P_{Rd} = 0{,}8 \cdot f_u \cdot \frac{\pi \cdot d^2}{4} \cdot \frac{1}{\gamma_v}$
JUS U. Z1. 010.	$R_d = 0{,}25 \cdot d^2 \cdot \sqrt{\beta_{b28} \cdot E_b}$	$R_d = 0{,}7 \cdot \frac{\pi \cdot d^2}{4} \cdot \sigma_n$

3.3. Commentary on the regulation of the strength of the shear connector

On the basis of the given review of the expressions for the calculation of the characteristic shear strength of the shear connector, it can be concluded that the values are significantly different depending on the applied codebook's regulations [2]. These differences are the consequence of determination for the strength of the shear connectors via examination, with inevitable dissipation of the results due to the different testing conditions. Also the accepted partial and global safety coefficients in the used regulations are different.

Because of the generally accepted concept of limit states, the advantage is given to the flexible (ductile) shear connectors of the stud shear connectors type. If the quality and speed of installing of these shear connectors are taken into consideration, the tendency of their progressive usage in the area of building constructions and bridge construction is obvious.

Taking into account the previously mentioned expressions for the strength of the shear connectors stud shear connectors, as illustration, in Figure 7 the comparative example of the strength for the ∅22 mm [1] shear connector is presented. The diagram displays the strength defined according to the criteria of permissible local concrete pressure, as well as to the criteria of permissible shearing along the cross-section of the shear connector. The values are given for the calculation of composite cross-section strength by the plasticity theory, without reducing the strength that is done for the calculation by the elasticity theory.

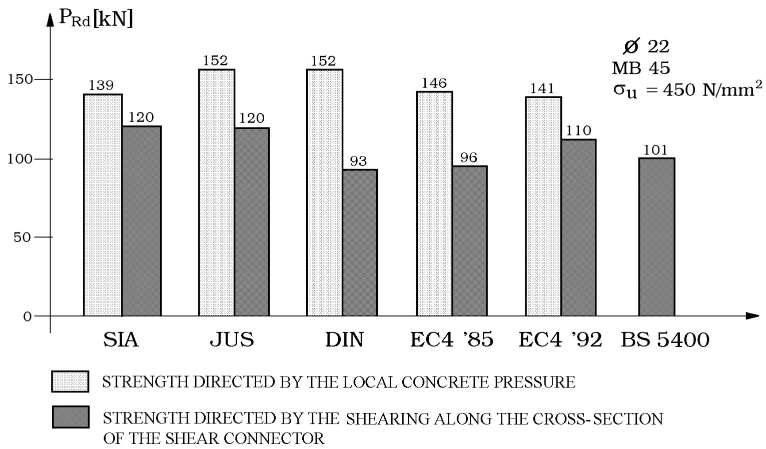

Fig. 7. Comparative review of the stud shear connectors diameter ∅22 mm according to the contemporary regulations

Figure 8 gives the percentage ratio of the stud shear connectors strength in comparison to standard JUS U. Z1 010. It can be perceived that the values for the strength of these shear connectors in international regulations are either the same or smaller than JUS, and that for this type of the shear connectors and the treated material strength (steel and concrete) the criteria of shearing along the cross-section of the shear connector is more strict.

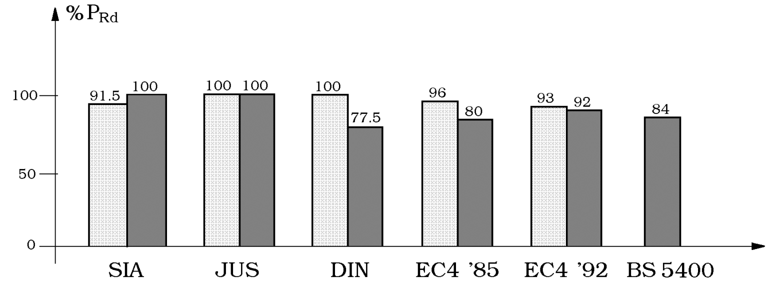

Fig. 8. Percentage ration of the stud shear connector's strength in comparison to standard JUS U. Z1. 010

The strength of stud shear connectors at composite beams with profiled sheet

The shearing force at composite beams with profiled sheet is not introduced directly through the base of the shear connect, but is transferred onto the shank of the shear connector (force P_B). The increase of load produces crushing of concrete in front of the shear connector and transfer of shearing force exclusively via bending. The maximum load creates two plastic areas (Fig. 9) at "a" distance, which defines the capacity of the connection. As in the case of composite beams with solid plates, due to the deformation of the shear connector δ, the tensile forces will occur in the shear connector itself (especially its head), that is pressure force in concrete. The horizontal component of the tensile force, marked with P_Z, has the bearing function, and also contains the friction forces occurring at the contact of the damaged concrete and steel flange.

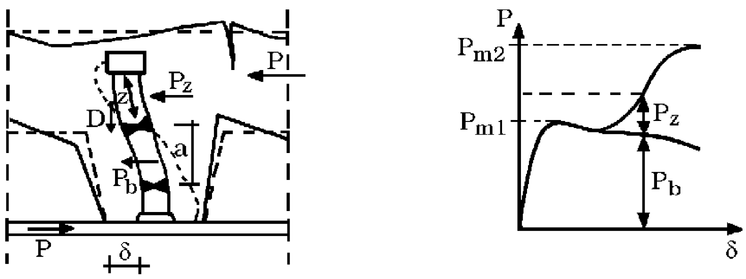

Fig. 9. Strength of the shear connectors with profiled sheet

The maximum strength P_{m2} is reached either due to the failure of concrete, or due to the failure of the shear connector above the weld. However, if the depth to which the shear connector is installed in the concrete slab is insufficient, a premature failure of the concrete ribs can occur, and it is marked as P_{m1} strength and in that case the upper plastic joint cannot form, resulting in the decrease of ultimate strength.

According to Eurocode 4 the strength of the shear connector is determined as with profiled sheet with the reduction with the k_t factor, and the difference is made depending on the direction of sheet alignment in respect to the steel beam, whether it is perpendicular of parallel.

In case when the profiled sheets are perpendicular to the axis of the beam, the strength is defined with the reduction factor k_t .

$$P_{tRd} = k_t \cdot P_{Rd} \tag{2}$$

where is: $$k_t = \frac{0{,}7}{\sqrt{n_R}} \cdot \frac{b_a}{h_p} \cdot \left[\frac{h}{h_p} - 1\right] \le \begin{cases} 1{,}0 \text{ za } n_R = 1 \\ 0{,}8 \text{ za } n_R = 2 \end{cases}$$

In case when the profiled sheets are parallel to the axis of the beam, the strength is determined by the reduction factor k_l .

$$P_{lRd} = k_l \cdot P_{Rd} \tag{3}$$

where is: $$k_1 = 0{,}6 \cdot \frac{b_0}{h_p} \cdot \left[\frac{h}{h_p} - 1\right] \le 1{,}0$$

maximum height of the shear connector

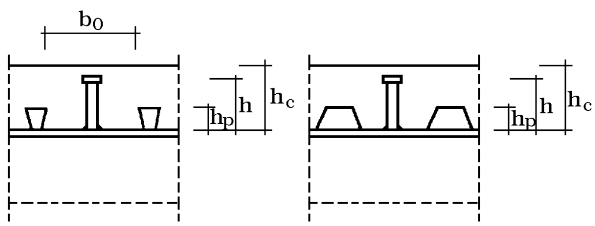

Fig. 10. Head stud shear connector in concrete rib cell

As to the installment manner, the strength is smaller if the sheets have prepared slots for shear connectors, because the strength of the profiled sheet is not activated. In this case the given expressions cannot be applied because Eurocode 4 defines the strength for the case of welded stud shear connector, where the profiled sheets are placed at the beam, but the shear connectors are welded afterward.

4. CONCLUSION

The strength of the shear connector is dictated by the criteria based on the exceeding of permissible load in the shear connector itself, the seam which connects it to the upper flange of the steel beam and the exceeded load in the surrounding concrete.

A large number of forms and significant differences in the conditions under which the shear connectors exist in the composite structures caused differences in the analytic formulation of their strength. This can be perceived in the example of these stated regulations. The general recommendation for accurate definition of the shear connector strength is the experimental proof.

Our comparative analysis has determined that JUS standing regulations for analytic determination of shear connector strength have very rational criteria in respect to the Europian standards that are mostly stricter or equal.

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STATIČKA NOSIVOST MOŽDANIKA U SPREGNUTIM NOSAČIMA

- ANALIZA PROPISA I ISTRAŽIVANJA -

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U radu je dat pregled najznačajnijih analitičkih izraza, na osnovu savremene literature razvijenih zemalja, za određivanje nosivosti moždanika kod spregnutih nosača čelik-beton. Prikazan je mehanizam mogućeg loma i osnovni kriterijumi na osnovu kojih se definiše nosivost moždanika kod punih ploča i ploča sa profilisanim limom. Posebna analiza izvršena je kod izraza i preporuka koje daje Evrokod 4 u oblasti nosivosti moždanika, elastičnih i krutih. Za sve prikazane propise daje se komparativna analiza sa našim (JUS) važećim standardom koji tretira ovu oblast. Uz uporedni pregled pravilnika dat je komentar o nosivosti moždanika u spregnutim nosačima.