

Theoretical research of the layout of shear studs on steel-concrete composite beams

Kristyna Hrabovska^{1*}

¹Brno University of Technology, Faculty of Civil Engineering, Institute of Metal and Timber Structures, Veveri 95, 602 00 Brno, Czech Republic

Abstract. This research is focused on the distribution of shear studs on steel-concrete composite beams. In practise, two different centre to centre spacings of coupling elements are commonly used, depending on the shear force. The main aim of this work is to find the best position on the beam to change the axial distance of the coupling elements, so that the smallest possible number of them can be used. Making a change at this point on the beam will ensure the most economical solution for the amount of the shear studs used as well as their appropriate utilization. In this work, equations for the design of the amount and the placement of the coupling elements on the beam, which can speed up the design in practice, were derived. In addition, the influence of the individual input parameters of the calculation on the distribution of shear studs was also investigated.

1 Introduction

Steel-concrete constructions use the favourable properties of the two materials: the high tensile strength of steel and conversely the high compressive strength of concrete. For the active interaction of the steel profile and the concrete slab, it is necessary to ensure their effective connection. Coupling elements, which can have different shapes, are used for this purpose. The Eurocode 4 [1] for the design of composite structures only contains an assessment procedure for welded shear studs with head, which is the most often used type of shear couplings. Their advantage over other types of coupling elements is their easy and quick connection and identical properties in all direction due their symmetrical shape.

Research focused on the optimization of coupling elements and development of new types is in progress in many countries. Linear shear couplings are often used in bridge structures. The linear type is e.g., a puzzle-like cut of web of the steel profile, which ensures the connection with the concrete slab. Research [2] dealing with the shape of the individual dowels, specifically, the radius of their rounding, was conducted at the Czenstochowa University of Technology in Poland. Experiments focused on the fatigue of the rib shear connectors were carried out by a united team from Germany and Belgium at the university in Aachen [3]. The researchers examined rib connectors with clothoid shaped dowels and exposed them to cyclic loading. Data from the experiment should be used to predict the service life of the structures. Another research effort is to achieve the

* Corresponding author: hrabovska.k@fce.vutbr.cz

demountability of composite structures and the possibility of reusing its parts after the end of their service life. This is related to the development of removable coupling elements, e.g., blind bolts. Experimental measurements of the load-bearing capacity of various blind bolts and their comparison with shear studs were carried out at the University of Isfahan in Iran [4]. This research tested bolts of different diameters and strength classes. The results show that the initial stiffness of the beam with demountable coupling elements is higher than the beam with welded shear studs. On the other hand, a beam with blind bolts exhibits an earlier slip and nonlinear behaviour. A similar experiment was performed at the Guangzhou University in China [5]. Here, the researchers investigated the influence of the individual input parameters on the load-bearing capacity of blind bolts. Specifically, the parameters were the size of the preload, the diameter of the bolt, the strength class of bolts and the size of pre-drilled hole. The obtained data served to create a model for a more detailed parametric study. Joint research by a team from Iran and Australia [6] was focused on the cyclic behaviour of bolted shear connectors. Retrofitted coupling elements were examined in a united work of Australian universities [7]. This work compared classic shear studs and blind bolts. Retrofitted shear couplings can be used in reconstruction of construction. Most research efforts deal with the optimization of the shape of the coupling element and do not pay the attention to their distribution on the beam. The layout of shear couplings was examined on Kuming University of Science and Technology in China [8]. The researchers compared the magnitude of force, slip and deformation on a two-span continuous beam with two different centre to centre spacings of shear studs. The results were compared with a beam with an equal distribution of the coupling elements.

The distance between the shear connectors is directly dependent on the shear force on the beam. The denser location is therefore situated near the supports, where the greatest shear force occurs. This force decreases towards the centre of the span, and thus the centre to centre spacing of the coupling elements gradually increase. If all the distances were different from each other, the assembly would be very time-consuming. Thus, only two different spacings of shear studs are used in practise. The aim of this research is to follow up on the previous works [9] and [10] and to find out how which parameters affect the distribution of coupling elements. At the same time, we also try to find the most suitable position on the beam to change the centre to centre spacing of shear studs, so that shear coupling are used effectively and the smallest possible number of them can be used.

2 Methods

There are two types of the coupling calculation – elastic and plastic. Plastic calculation is possible for the 1st and 2nd cross-section class and allows to take in account the redistribution of the shear force to all coupling elements. This allows the shear studs to be placed equally along the length of the beam. Specifically, it means, that the calculated amount of shear studs is equally distributed between the support and the point on beam with the maximum bending moment (e.g., for a simply supported beam loaded with uniformly distributed load, this is exactly half the span). As was already said in the previous work [10], the actual value of the load is not included in the plastic calculation. Instead, the maximum load-bearing capacity is considered, which leads to frequent oversizing of the beam. This can be prevented by using the partial coupling where the number of the shear couplings can be reduced. By modifying the relationship for the calculation of the partial coupling by substituting the actual value of the bending moment on the beam, the calculation gets closer to reality. On the other hand, the actual load enters the elastic calculation in the form of a shear force. Although the elastic calculation can be used for the 1st and 2nd cross-section class, it produces very conservative values. In fact, the coupling elements near the supports are used the most, because this is where the greatest shear force

occurs. Their use towards the center of the span gradually decreases along with the shear force. For this reason, the coupling elements are placed more densely near the supports. The spacing of the shear studs is proportional to the shear force on the beam. However, since the shear force does not figure in the plastic calculation, the elastic calculation must be used for the placement of the coupling elements.

When calculating in the elastic region, it is assumed that the shear force acting on one shear stud corresponds to the increase of the normal force in the concrete, which can be expressed as

$$V_{L,el} = \frac{V_{Ed} \cdot S_c \cdot s_1}{n \cdot I_i} \quad (1)$$

where V_{Ed} is the acting shear force, S_c is the first moment of concrete slab, s_1 is the centre spacing of shear studs, $n = E_a / E_{c,eff}$ is the working factor and I_i is the second moment of ideal cross-section.

According to the reliability condition, the ratio of the shear force and the number of the coupling elements in the transverse direction must be smaller than the design load-bearing capacity of one shear stud P_{Rd} . From this condition and from equation (1), a relationship can be derived for the calculation of the maximum possible centre to centre spacing of the shear couplings for the given force. The maximum shear force on the beam corresponds to the axial distance of the shear studs, which will be marked as $s_{l,min}$. As the shear force decreases, the centre to centre spacing of coupling elements increases further. Therefore, the axial distance of the shear studs corresponding to the maximum shear force on the beam is calculated as

$$s_{l,min} = \frac{P_{Rd} \cdot n_r \cdot n \cdot I_i}{V_{max} \cdot S_c} \quad (2)$$

where P_{Rd} is the design load-bearing capacity of the shear stud, n_r is the number of shear studs in transverse direction, n is the working factor, I_i is the second moment of ideal cross-section, V_{max} is the maximum shear force on the beam and S_c is the first moment of the concrete slab.

If the maximum shear force V_{max} corresponds to the centre to centre spacing of coupling elements $s_{l,min}$, then the force $V_{(x)}$ at any point x on the beam corresponds to the axial distance $s_{l,(x)}$.

The above equations apply in general to all beams. For a simply supported beam with a uniformly distributed load, the maximum shear force is calculated as

$$V_{max} = \frac{1}{2} qL \quad (3)$$

where q is the value of the uniformly distributed load on the beam and L is the span of the simply supported beam.

Similarly, the force $V(x)$ at any point of the beam can be expressed as

$$V_{(x)} = \frac{1}{2} qL - qx \quad (4)$$

where q is the value of the uniformly distributed load on the beam, L is the span of the simply supported beam and x is the distance from the support to the point on the beam where the centre to centre spacing of the coupling elements changes.

The number of shear studs on a section of a beam can be found as the length of a given section divided by the size of the centre to centre spacing used on that section. If two different sizes of the axial distance of the coupling elements are used on the beam, one corresponding to the maximum shear force and the other for the mid-span section corresponding to the force $V_{(x)}$ at the point x , where the axial distance of studs has changed, then the total number of shear couplings is calculated as

$$n = \frac{2x}{s_{l,min}} + \frac{L-2x}{s_{l,(x)}} \quad (5)$$

where L is the span of the simply supported beam, x is the distance from the support to the point on the beam where the centre to centre spacing of the coupling elements changes,

$s_{l,min}$ is smallest axial distance of the coupling elements on the beam corresponding to the force V_{max} and $s_{l,(x)}$ is the maximum possible axial distance of the coupling elements corresponding to the force $V_{(x)}$.

By substituting equations (3) and (4) into relationship (5) and other adjustments, the equation for calculating the number of shear studs is created depending on the distance from the support to the place where the centre to centre spacing of shear coupling will change. It can be seen from the equation that it is a quadratic function in the form

$$n = \frac{4}{s_{l,min} \cdot L} \cdot x^2 - \frac{2}{s_{l,min}} \cdot x + \frac{L}{s_{l,min}} \quad (6)$$

where L is the span of a simply supported beam, x is the distance from the support to the point on the beam where the centre to centre spacing of coupling elements changes and $s_{l,min}$ is the smallest axial distance of coupling elements on the beam corresponding to the force V_{max} .

The graph of a quadratic function is a parabola. Equation (6) can be easily converted into vertex form to obtain the coordinates of the vertex

$$V \left[\frac{L}{4}, \frac{3L}{4 \cdot s_{l,min}} \right] \quad (7)$$

where the first coordinate indicates the position on the beam where it is most appropriate to change the axial distance of shear studs, so that the smallest possible number of the studs can be used. The second coordinate indicates the specific minimum number of shear studs, when the centre to centre spacing of coupling elements is changed at the desired point.

It follows from the first coordinate of relation (7) that for a simply supported beam of any length loaded with a uniformly distributed load, it is always most advantageous to change the axial distance of the studs in the quarter of the span. This would of course be true under ideal conditions, where the maximum centre to centre spacing of the coupling elements can theoretically go to infinity when considering the shear force near the centre of the span. Normally, the axial distance of studs is limited by design principles. The maximum centre to centre spacing should not exceed the smaller of the values $6 \cdot h_c$ or 800 mm, where h_c is the height of the concrete slab. By combining equations (2) and (4), where the axial distance is replaced by the maximum permissible value, we create the relationship

$$x = \frac{1}{2}L - \frac{P_{Rd} \cdot n_r \cdot n \cdot I_i}{S_c \cdot s_{l,max} \cdot q} \quad (8)$$

where L is the span of the simply supported beam, P_{Rd} is the design load-bearing capacity of the shear stud, n_r is the number of the shear studs in transverse direction, n is the working factor, I_i is the second moment of the ideal cross-section, S_c is the first moment of the concrete slab, $s_{l,max}$ is the maximum allowable centre to centre spacing of shear studs according the design principles and q is the value of the uniformly distributed load on the beam.

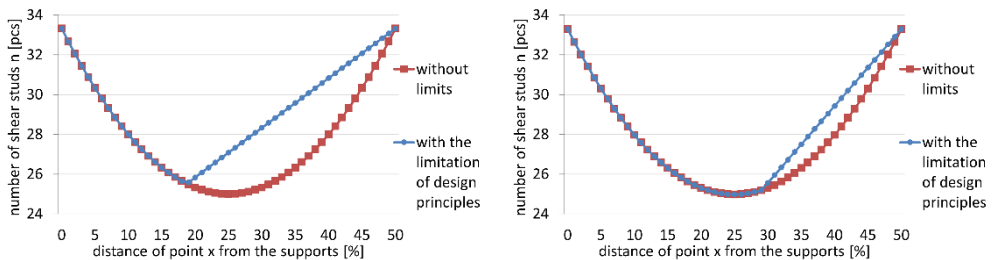


Fig. 1. Graphs showing the dependence of the number of shear studs on the change of their centre to centre spacing at the distance x from the edge of the simply supported beam without and with the limitation of design principles. Left for $x < L/4$ and right for $x > L/4$.

By modifying the equation (8), a form can be obtained in which it is evident that it is a linear function whose graph is a straight line. Limiting the centre to centre spacing of studs means that from a certain point on the beam, the axial distance can not be increased anymore. Graphically, it looks like a straight line that intersects the parabola at a certain point, as can be seen in Fig. 1. To find the minimum number of coupling elements on the beam, it is essential whether the straight line crosses the parabola before or after the vertex. If the intersection of the parabola and the straight line is beyond the vertex, the limit of design principles is irrelevant and the best position to change axial distance of studs is in the quarter of the beam. On the other hand, if the intersection is before the vertex, it means the limit of design principles have to be considered. Then the ideal position for the change of axial distance of studs is precisely at the intersection of these function, which is the value calculated by equation (8). This means that the best place on the beam to change the centre to centre spacing of the coupling elements is the smaller of values of $L / 4$ and the result of equation (8).

The calculation is a bit more complicated for continuous beams. Again, equations (1) and (2) apply. For simplicity, only beams with equally length of span are considered. Specifically, beams with 2 and 3 spans are further considered. The calculation here is complicated by the different magnitude of the shear force in the outer and inner supports, as well as by more options for arranging of the uniformly distributed load on the spans. For now, a uniformly distributed load along the entire length of continuous beams is considered.

For a beam with two equally sized spans, the maximum shear force is on the internal support with the value $V_{\max} = (5 / 8) qL$. The shear force at any point x on the beam is therefore calculated as $V_{\max} - qx$, where x is the distance from the inner support. There is a different value of the shear force above the outer and inner support. Therefore, it is not possible to consider changing the centre to centre spacing of studs at the same distance from outer and inner supports. A place must be found on the beam with the same value of the shear force. So, the distance x is measured from the inner support and the distance from outer supports for the change of the centre to centre spacing of the coupling elements (point on the beam with shear force of value $V_{(x)}$) is at a distance of $x - (1 / 4) L$, as shown in Fig. 2. From Fig. 2, the equation for the number of the shear studs on a beam with two equal spans loaded with a uniformly distributed load can be derived. Its form is similar to equation (5) for a simply supported beam, only the lengths of the individual sections are different. The equation is therefore as follows:

$$n = \frac{2x - \frac{1}{4}L}{s_{l,\min}} + \frac{\frac{5}{4}L - 2x}{s_{l,(x)}} \quad (9)$$

where L is the length of the span of the two-span beam, x is the distance from the inner support to the point on the beam where the centre to centre spacing of coupling elements changes, $s_{l,\min}$ is the smallest axial distance of the coupling elements on the beam corresponding to the force $V_{\max}$ and $s_{l,(x)}$ is the maximum possible axial distance of the coupling elements corresponding to the force $V_{(x)}$.

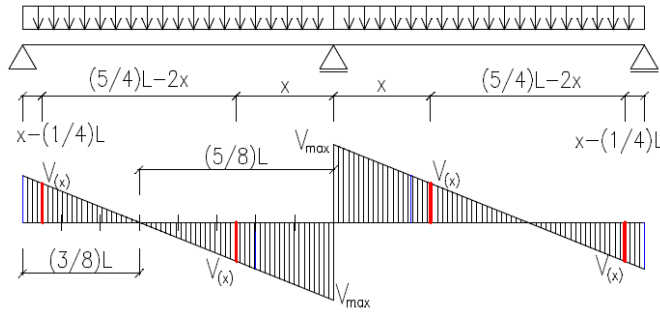


Fig. 2. A continuous beam with two spans of the same length loaded with a uniformly distributed load with a marked distance from supports to points on the beam with shear force of value $V(x)$.

By substituting of calculations for $V_{(max)}$ and $V_{(x)}$, equation (9) can be modified to the form

$$n = \frac{32}{5 \cdot L \cdot s_{l,min}} \cdot x^2 - \frac{4}{s_{l,min}} \cdot x + \frac{2L}{s_{l,min}} \tag{10}$$

where L is the length of the span of the two-span beam, x is the distance from the inner support to the point on the beam where the centre to centre spacing of the coupling elements changes, $s_{l,min}$ is the smallest axial distance of the coupling elements on the beam corresponding to the force V_{max} .

It is again a quadratic function, only with different parameters. Equation (10) can be converted into vertex form, where the first coordinate indicates the ideal position on the beam for the change of the axial distance of the studs under ideal conditions. For a beam with two spans, it is $(5 / 16) L$ from the inner support (i.e. $(1 / 16) L$ from the outer support). By introducing the limit of the design principles into equation (2) with the shear force $V_{(x)}$ applied, the equation can be obtained for determining the ideal position for centre to centre spacing of studs in the form

$$x = \frac{5}{8} L - \frac{P_{Rd} \cdot n_r \cdot n \cdot I_1}{s_{l,max} \cdot S_c \cdot q} \tag{11}$$

where L is the length of the span of the two-span beam, P_{Rd} is the design load-bearing capacity of the shear stud, n_r is the number of the shear studs in transverse direction, n is the working factor, I_1 is the second moment of the ideal cross-section, S_c is the first moment of the concrete slab, $s_{l,max}$ is the maximum allowable centre to centre spacing of the shear studs according the design principles and q is the value of the uniformly distributed load on the beam.

As with a simply supported beam, this is a linear function, graphically a straight line. And again, it is decisive whether it intersects the parabola before or after the vertex. The ideal position for the change of the axial distance of the coupling elements can then be determined as the smaller of the values of $(5 / 16) L$ and the result of relation (11), where x is the distance measured from the inner support.

The same method can be used for a continuous beam with three equal spans loaded with a uniformly distributed load. In this case, the maximal shear force is on the inner support too. Its value is $V_{max} = 3 / 5 qL$. Then the shear force $V_{(x)}$ at any point x of the beam is equal to $V_{max} - qx$, where x is the distance from the inner support measured towards the edge of the beam. Fig. 3 shows the length of the individual sections of the beam to places with the same value of the shear force $V_{(x)}$. From Fig. 3 we derived the equation for the number of the studs on the beam with three spans

$$n = \frac{10}{L \cdot s_{l,min}} \cdot x^2 - \frac{6}{s_{l,min}} \cdot x + \frac{3L}{s_{l,min}} \tag{12}$$

where L is the length of the span of the three-span beam, x is the distance from the inner support measured towards the edge of the beam to the point on the beam where the centre

to centre spacing of the coupling elements changes, $s_{l,min}$ is the smallest axial distance of the coupling elements on the beam corresponding to the force V_{max} .

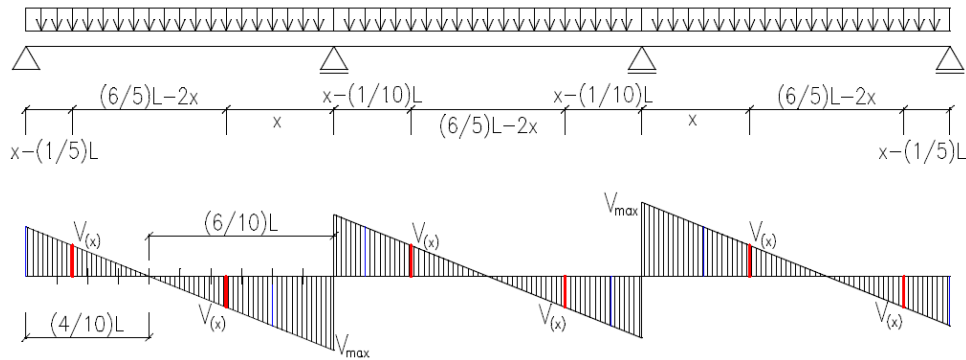


Fig. 3. A continuous beam with three spans of the same length loaded with a uniformly distributed load with a marked distance from supports to points on the beam with shear force of value $V(x)$.

As in the previous case, relation (12) is a quadratic function, where first coordinate of the parabola's vertex gives the ideal point for the changing of the centre to centre spacing of the shear studs without affecting the design principles. Specifically, it is a value of $(3 / 10) L$ from the inner support towards to edge of the beam. The distance from the outer support and in the middle span can be read from Fig. 3. Again, by introducing the limit of the design principles into equation (2) with the shear force $V_{(x)}$ for the three-span beam applied, the equation can be obtained for determining the ideal position for the centre to centre spacing of the studs in the form

$$x = \frac{3}{5}L - \frac{P_{Rd} \cdot n_r \cdot n \cdot I_i}{s_{l,max} \cdot S_c \cdot q} \quad (13)$$

where L is the length of the span of the three-span beam, P_{Rd} is the design load-bearing capacity of the shear stud, n_r is the number of the shear studs in transverse direction, n is the working factor, I_i is the second moment of the ideal cross-section, S_c is the first moment of the concrete slab, $s_{l,max}$ is the maximum allowable centre to centre spacing of the shear studs according to the design principles and q is the value of uniformly distributed load on the beam.

So, the ideal place on the beam to change the axial distance of coupling elements is found as the smaller of the values of $(3 / 10) L$ and result of relation (13), where x is the distance from the inner support towards to edge of the beam.

As mentioned above, this is not always applied for continuous beam, as it depends on the distribution of the uniformly distributed load on individual spans of the beam. For a two-span beam, if only one span is loaded, this position obtained from the vertex of parabola can shift by $(1 / 16) L$, i.e., 6.25 % of the span length. For a three-span beam considering different placement options for uniformly distributed loads, the position of the ideal point on the beam can shift by a maximum of $(1 / 20) L$, i.e., 5 % of span length. The distance of places on the beam with marked the same value of $V_{(x)}$ for different configurations of loads can be seen in Fig. 4.

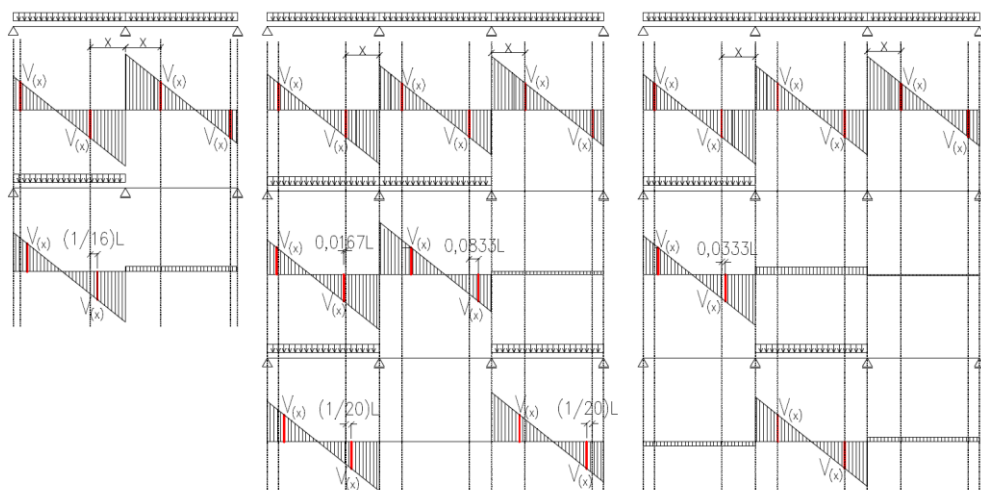


Fig. 4. Options for the distributing of the uniformly distributed load on individual spans of a continuous beam with two and three spans of same length.

3 Results

The derived equations were inserted into a spreadsheet and compared with the result of a parametric study, where the number of the coupling elements on the beam was calculated. A parametric study was carried out for a simply supported beam and for continuous beams with two and three spans of the same length. The distance x was varied, which indicates the position on the beam, where the centre to centre spacing of the shear studs was changed. Specifically, the distance x was increased in units of percentages of span length.

As basic samples for the parametric study, beams from IPE 300 profile made of steel S235 and concrete slabs of height 80 mm and effective width 2200 mm, made of concrete C25/30 were considered. The coupling was ensured by shear studs of length of 50 mm, shank diameter of 16 mm made from strength class 4.8. The beams were assumed with a length of spans of 10 m, loaded with a uniformly distributed load of 15 kN/m.

For a simply supported beam, the individual input parameters were further changed and their effect on the position of point x was observed. The length of the span and the value of the load have a direct influence on the ideal position for changing the axial distance of the coupling elements. However, other parameters can also affect the position of point x . These are the variables that will affect the load-bearing capacity of the shear stud or the value of the maximum centre to centre spacing of the coupling elements, e.g., the strength of the concrete, the height of the concrete slab, the size of the steel profile or the strength class and the dimensions of shear studs.

Finally, the minimum amount of the coupling elements obtained by the elastic calculation using the point x on the beam to change of centre to centre spacing of shear studs and the number of coupling elements from the plastic calculation considering the partial coupling were compared.

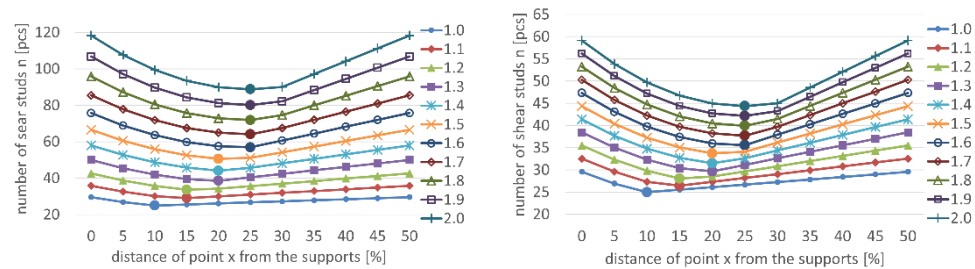


Fig. 5. Graphs of the dependence of the amount of coupling elements on the distance of point x from the edge of the simply supported beam for the percentage increase in the span length (left) and uniformly distributed load (right). Minimum values are marked in the graphs.

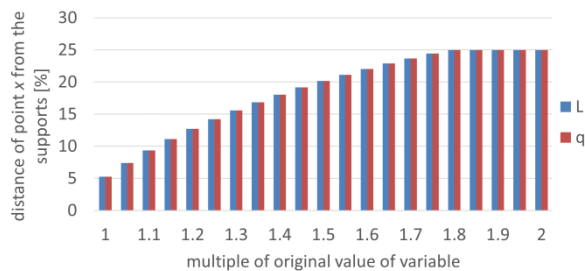


Fig. 6. Graph comparing the position of point x depending on the percentage increase in the span length and the value of the uniformly distributed load.

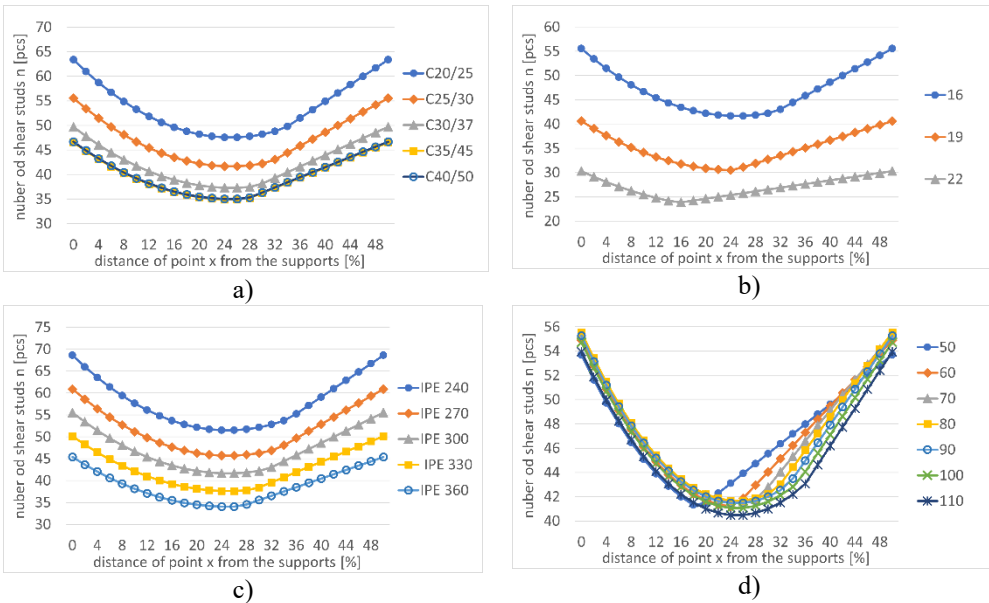


Fig. 7. Graphs of dependence of the number of the coupling elements on the position of point x for changing individual input parameters. Specifically, graph a) for the change in the strength of concrete, graph b) for the change in the diameter of shank of shear stud, graph c) for the change in the IPE profile and graph d) for the change in the height of the concrete slab.

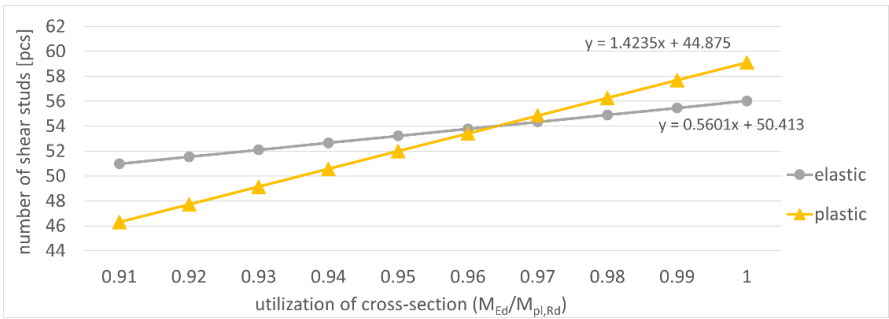


Fig. 8. Graph comparing the number of shear studs depending on the utilization of the cross section for plastic and elastic calculation.

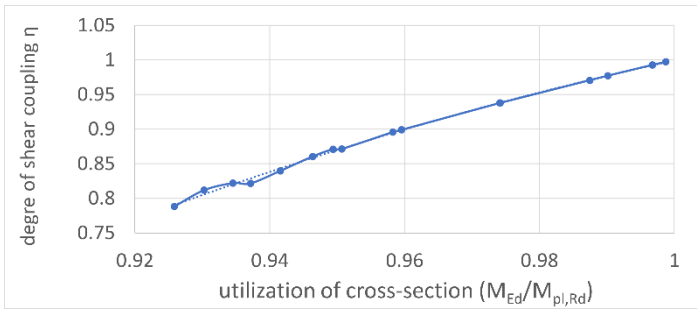


Fig. 9. Graph showing the dependence of the degree of shear coupling on the utilization of the cross section of the composite beam (the ratio of the bending moment to the plastic load-bearing capacity of the cross-section).

4 Discussion

The results of the parametric study prove the correctness of the derived relations for a simply supported beam as well as for the continuous beams with two and three spans. In the parametric study, the number of the coupling elements on the beam was calculated with different position of point x , where the axial distance of the coupling elements was changed. The position of point x was changed by units of percent of length of the beam span. The minimum amount of the shear studs was achieved by changing the centre to centre spacing of the coupling elements at the point of the beam, which is equal to the value from the above relationships, specifically, the value from relation (8) for the simply supported beam, from relation (11) for the two-spans beam and the relation (13) for the three-span beam. The correctness of derived equation can also be seen from the graphs in Fig. 5. The dependence of the amount of the shear studs on the position of point x for a simply supported beam is shown there. It is clear from the shape of the curves, that there are parabolas, but only up to the certain point, where the maximum axial distance of the shear studs according to the design principles is reached. From this point the parabola becomes a straight line. The shapes of the function are also similar in the case of the two-span and three-span continuous beam.

In Fig. 5 we can also see that the percentage increase in the length of the beam and the value of the uniformly distributed load causes a different increase in the number of the coupling elements. When the span of the beam changes the amount of the shear studs increases faster than when the load changes. However, regarding the ideal position for changing the centre to centre spacing of the coupling elements, for the same percentage increase in both quantities, the position on the beam is the same. (Locations with the

minimum number of the coupling elements are marked in the graphs.) This dependence is better visible in the graph in Fig. 6, where the position of point x is shown at the percentage increase in the length of the beam and the value of load. The same dependence applies to both parameters. At the same time, the graph shows that increasing the distance x from the supports stabilizes at a value of 25 % of the span and does not increase further. This is due to the fact that here is an extremum of the function for a simply supported beam and there is no more advantageous position for changing the axial distance of the coupling elements further up the beam.

The values of the input parameters were changing in the parametric study and their influence on the position of point x on the beam was investigated. The height of the concrete slab, the strength of the concrete, the strength of the steel, the size of the steel profile and the dimensions and strength of the shear studs were considered. These parameters have only a limited effect on the position of point x because they interact with each other. E.g., the load bearing capacity of shear studs P_{Rd} (which occurs in the calculation of the position of x) is calculated as the smaller of two values and depends on which one enters the calculation. In Fig. 7 there are graphs for the position of point x on the beam depending on the selected parameters. Moving the position for the ideal change of the axial distance of the coupling elements closer to the support will cause an increase in the strength of the concrete (Fig. 7a), the height or diameter of the shank of the shear studs (Fig. 7b) or an increase in the steel profile (Fig. 7c). A smaller value of x is also achieved by reducing the span of the beam, the value of the uniformly distributed load, the height of the concrete slab (Fig. 7d) and the effective width of the slab.

At the end, a comparison of the minimum amount of the coupling elements in the elastic and plastic calculations was made. For the elastic calculations, the number of the shear studs was calculated using point x on the beam for the ideal the centre to centre spacing change. For plastic calculations, the partial coupling was considered. The number of the shear studs was calculated for the values of the bending moment on the beam corresponding to the percentage quotient of the plastic load-bearing capacity $M_{pl,Rd}$ from 50 % utilization to the full capacity. This means that in some cases the elastic calculation would no longer comply here. A parametric study was carried out for different beams, where the height of the concrete slab, the strength class of concrete and steel and the size of the IPE profile was varied. For each configuration, the size of the bending moment (equal to the percentage value of the plastic load-bearing capacity) was determined, when the same number of shear studs is used in both calculations, as can be seen in the graph in Fig. 8. These intersections of plastic and elastic calculations were found to be dependent on the degree of shear coupling. This dependence is shown in the graph in Fig. 9. In the graph we can see that with a degree of shear coupling from 0.79 to 0.99, the match of the number of shear studs from both calculations is achieved when the value of the bending moment is approx. 92-99 % of $M_{pl,Rd}$. The beam no longer complies in the elastic calculations for this value of the bending moment. On the other hand, the elastic calculations to cross-section classes 1 and 2 are quite conservative. This dependence proves that even in plastic calculations, the coupling elements can be placed using the elastic area, because in both cases, similar numbers of the shear studs are used. This means that there is a more dense placement of the shear studs at the supports. By redistributing the shear studs, a better utilization is achieved than with an even distribution.

5 Conclusion

The results of the research proved the correctness of the derived relations for the ideal position on the beam of the changing the centre to centre spacing of the coupling elements. This was done for the simply supported beam as well as for the two-span and three-span

continuous beam with spans of the same length. It is always the smaller of the two values, where the first is given by the extremum of the function, i.e., the vertex of the parabola, and the second follows from the result of the equation, according to the type of beam. The span of the beam and the value of uniformly distributed load have a direct effect on the determination of the position x . The location of load on the individual spans of a continuous beam can also influence the ideal position for the change of the axial distance of the shear studs. In this case, the point x on the beam moves by the maximum of 6.25 % of the span for the two-span beam and by the maximum of 5 % of the length of the span for the three-span beam. The ideal position for changing the centre to centre spacing of the coupling elements can also be affected to a limited extent by other parameters such as the strengths of the materials or the dimensions of the individual parts of the composite beam or the shear stud.

Furthermore, the research shows that even in the case of cross-section classes 1 and 2, where the beam is commonly calculated by plastic calculations (the elastic calculation would not be comply), the coupling elements can be redistributed using the elastic calculation. This is possible due to the approximate matching of the number of the shear studs in the elastic and plastic calculation using partial coupling. The shear studs can be located more densely near the supports and with a greater axial distance in the middle of the span. In this way, we achieve a better use of the individual coupling elements than in the case of their equal distribution on the beam, when the force redistribution is assumed.

This research was only concerned with beams loading with uniformly distributed load. The same principle can be probably also used for other types of beams with different type of load.

The article was prepared as a part of the Specific University Research project at the Faculty of Civil Engineering of the Brno University of Technology No. FAST-S-22-8006 and No. FAST-S-23-8317.

References

1. EN 1994-1-1: Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules for building, Brussels, CEN, 2004
2. P. Lacki, P. Kasza, K. Adamus, Optimization of composite dowels shape in steel-concrete composite floor, *Comp. Struct.*, Vol. **222**(2019), 110902, Elsevier Ltd., ISSN: 0263-8223, <https://doi.org/10.1016/j.compstruct.2019.110902>
3. G. Christou, J.Hegger, M. Classen, Fatigue of clothoid shaped rib shear connectors, *J. of Const. St. Rese.*, Vol. **171**(2020), 106133, Elsevier Ltd., ISSN: 0143-974X, <https://doi.org/10.1016/j.jcsr.2020.106133>
4. A. Ataei, M. Zeynalian, A study on structural performance of deconstructable bolted shear connectors in composite beams, *Struct. [online]*, **148** (2018), 508-254, ISSN: 23520124, [doi:10.1016/j.struc.2020.11.065](https://doi.org/10.1016/j.struc.2020.11.065)
5. Y. Zhang, B. Chen, A. Liu, Y. Pi, J. Zhang, Y. Wang, L. Zhong, Experimental study on shear behaviour of high strength bolt connection in prefabricated steel-concrete composite beam, *Compos. Part B: Engineering [online]*, **159** (2019), 481-489, ISSN: 13598368, [doi:10.1016/j.compositesb.2018.10.007](https://doi.org/10.1016/j.compositesb.2018.10.007)
6. A. Ataei, M. Zeynalian, Y. Yazdi, Cyclic behaviour of bolted shear connectors in steel-concrete composite beams, *Eng.Struc.*, Vol. **198**(2019), 109455, Elsevier Ltd., ISSN: 0141-0296, <https://doi.org/10.1016/j.engstruct.2019.109455>
7. I.E.J. Handerson, X.Q. Zhu, B. Uy, O. Mirza, Dynamic behaviour of steel-concrete composite beams retrofitted with various bolted shear connectors, *Engineering*

- Structures [online], **131** (2017), 115-135, ISSN: 01410296,
doi:10.1016/j.engstruct.2016.10.021
8. Y. Luo, D.H. Zhou, B. Duan, Study on the influence of step changed spacing of shear stud connector on the behaviour of continuous composite beam, IOP Conference Series: Earth and Environmental Science [online], **153** (2018), ISSN: 1755-1307, doi:10.1088/1755-1315/153/5/052060
 9. K. Hrabovská, J. Břečka, Theoretical research of dimensional optimization and choice of material strength in steel-concrete composite beams, IOP Conf. Ser.: Mater. Sci. Eng., **1209**(2021), 012057 doi:10.1088/1757-899x/12091/1012057
 10. K. Hrabovská, Theoretical research of the influence of changes in input parameters on load-bearing capacity and quantity of shear coupling, Conference Young Scientist 2022, 27-29 June, Čingov, Slovakia (2022) (to be published)