EXTENSION OF THE RESEARCH ON THE LAYOUT OF SHEAR STUDS ON A STEEL-CONCRETE COMPOSITE BEAM

Kristýna Hrabovská[*,1]

[*1]176153@vutbr.cz
[1]Brno University of Technology, Faculty of Civil Engineering, Institute of Metal and Timber Structures, Veveří 95, 602 00 Brno, Czech Republic

Abstract

Appropriate placement of shear studs on the steel-concrete beam can provide their better use. A denser placement is advisable for supports where the shear force is higher. In practice, only two or three different spacings are most often used. The aim of this research was to investigate whether more different spacings of coupling elements would still have a significant effect on the quantity and effective use of studs and the possibly finding the ideal location to make these spacing changes.

Keywords

Steel-concrete composite beam, shear studs, placement, centre-to-centre spacing, parametric study

1 INTRODUCTION

Steel-concrete composite beams have been used more frequently, especially to overcome longer spans. They take advantage of the favourable properties of the used materials to create an effective and economical cross-section. The design of steel-concrete structures is governed by Eurocode 4 [1] and Eurocodes 2 and 3 [2], [3]. The coupling elements have a major influence on the correct function of the composite beam. Today, steel studs with heads are most frequently used due to their simple installation and equal properties in all directions.

A number of researches have focused on coupling elements. A significant number of them have investigated the design of new types or the properties of existing ones. A smaller part of the research focuses on their distribution on the beam. The distribution of the coupling elements has been investigated, for example, in the research of the team from Iraq [4]. They investigated 4 configurations of the shear stud distribution on the beam. A two-row arrangement, a single-row arrangement, an alternating arrangement of one and two studs on the beam, and a single-row arrangement staggered along the longitudinal axis. The beam with two rows of studs had a higher bending strength capacity compared to other beams. The beam with alternating studs along the longitudinal axis had the worst results. The new layout design for the two-field beam was proposed by Zona, Leoni and DallAsta from the University of Camerino [5]. The suggested changing the axial spacing of the coupling elements in the places of maximum/minimum and zero moments. Hassanin, Shabaan and Elsheikh [6] focused on fatigue loading. Using FE analysis, they compared simply supported beams with different values of shear capacity. At the same time, they compared the results with a beam where the total number of studs was the same but the number of studs in the centre of the beam was half the density of the supports. They proved that the layout with denser placement at the supports has a significant effect on improving the beam properties. The research carried out in China [7] focused on the slip and deflection of composite beams. It investigated the results for a simply supported beam with 4 different types of loads (point and continuous). At the same time, beams with 2, 3, and 5 sections with different axial distances of coupling elements were considered. The research has shown the use of different types of loads and that splitting the beam into multiple sections reduces deflection and slip. Experimental research was conducted in Kenya [8]. They investigated 4 types of stud arrangement on the beam. Fully coupled beam and partially coupled beam with even distribution of studs and with their dividing into two and three sections with different spacing of studs while keeping the same total number of studs on the beam. The beams were loaded by four-point bending. They found that the fully coupled beam had the highest bending capacity. However, they found that for partial coupling, splitting into multiple sections had a beneficial effect on the load capacity and it approached the values of the beam with full coupling. The stepped layout of the shear joints has significantly improved resistance to

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deflection. In addition, it was found that as the beam was divided into more sections, less end slippage occurred compared to a uniform distribution.

The aim of this research is to build on previous work [9], where a beam was divided into 3 sections and the most suitable position for changing the individual spacings was investigated. The research aims to find out if the same calculation assumptions are applicable to dividing a beam into multiple sections. The next goal is to find out whether this further subdivision is useful or whether its benefit is already negligible due to the greater labour involved in assembly work.

2 METHODOLOGY

This research is related to previous work [9] where the effect of three different coupling element spacings was investigated. It is based on the same conclusion that the plastic calculation does not account for the actual load of the beam but assumes its maximum load-bearing capacity. Therefore, the plastic calculation leads to a significant oversizing. In the plastic design, the redistribution of the force is considered, and the studs are therefore evenly distributed on the beam. On the other hand, the elastic calculation considers the actual shear force, which varies along the length of the beam. The highest values are reached at the supports and decrease towards the centre of the beam for a simple beam. The maximum shear force $V_{\max}$ corresponds to the spacing of the connecting elements $s_{\mathrm{l,min}}$. Then, for a uniformly distributed load at any point in the beam distant from the support by a length x, the force $V_{(\mathrm{x})}$ corresponds to the stud spacing value $s_{\mathrm{l,(x)}}$. As mentioned in the previous research, the total number of studs on the beam is calculated as the sum of the lengths of each section divided by the shear stud spacing on the given section. Consider a beam with four different axial spacings of coupling elements as shown in Fig. 1. The equation for calculating the total number of coupling elements on the beam is:

$$n = \frac{2x}{s_{\mathrm{l,min}}} + \frac{2y}{s_{\mathrm{l,(x)}}} + \frac{2z}{s_{\mathrm{l,(y)}}} + \frac{L - 2x - 2y - 2z}{s_{\mathrm{l,(z)}}} \tag{1}$$

where x is the distance from the support to the point on the beam where the centre-to-centre spacing of coupling elements first changes, y is the distance from point x toward the centre of the beam where the spacing of shear studs changes for the second time, z is the distance from point y toward the centre of the beam where the spacing of shear studs changes for the third time, L is the span of a simply supported beam, $s_{\mathrm{l,min}}$ is the axial distance of coupling elements corresponding to the shear force $V_{\max}$, $s_{\mathrm{l},(x)}$is the axial distance of coupling elements corresponding to the shear force $V_{(x)}$, $s_{\mathrm{l},(y)}$ is the axial distance of coupling elements corresponding to the shear force $V_{(y)}$ and $s_{\mathrm{l},(z)}$ is the axial distance of coupling elements corresponding to the shear force $V_{(z)}$. All lengths must be in the same units.

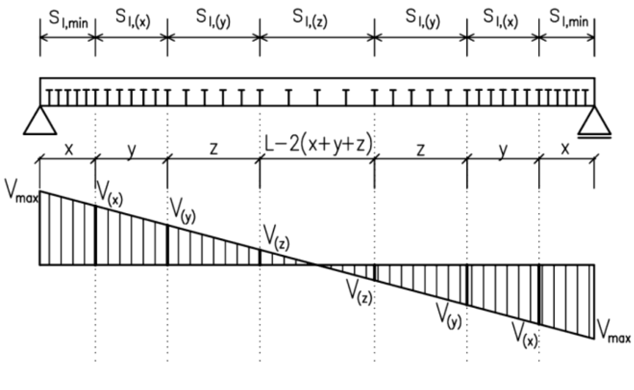

Fig. 1 A scheme of the shear stud distribution on a beam using four spacings where the spacing change is at distances x, y and z.

The new equation is obtained by modifying the equation (1) in the form

$$n = \frac{4}{s_{\mathrm{l,min}} \cdot L} \cdot x^2 + \frac{4}{s_{\mathrm{l,min}} \cdot L} \cdot y^2 + \frac{4}{s_{\mathrm{l,min}} \cdot L} \cdot z^2 + \frac{4}{s_{\mathrm{l,min}} \cdot L} \cdot xy + \frac{4}{s_{\mathrm{l,min}} \cdot L} \cdot xz + \frac{4}{s_{\mathrm{l,min}} \cdot L} \cdot yz - \tag{2}$$

$$-\frac{2}{s_{\text{l,min}}}\cdot x-\frac{2}{s_{\text{l,min}}}\cdot y-\frac{2}{s_{\text{l,min}}}\cdot z+\frac{L}{s_{\text{l,min}}}$$

It can be seen that this is a quadratic function but of 4 variables. For 2 different axial spacings of the shear studs, the equation came out as a parabola and for three spacings it was a quadratic, namely an elliptic paraboloid. A function of 2 variables can be easily visualized in the plane. Likewise, the 3 variables in space. Unfortunately, the function of 4 variables cannot be represented so easily. But even so, it remains certain that there is a point where the minimum is reached and where it is therefore most suitable to change the centre-to-centre spacing. Using the affine properties of the quadrics described in [10], the resulting equation (2) can be rewritten into a matrix

$$\begin{pmatrix} \frac{4}{s_{\text{l,min}}\cdot L} & \frac{2}{s_{\text{l,min}}\cdot L} & \frac{2}{s_{\text{l,min}}\cdot L} & -\frac{1}{s_{\text{l,min}}} \\ \frac{2}{s_{\text{l,min}}\cdot L} & \frac{4}{s_{\text{l,min}}\cdot L} & \frac{2}{s_{\text{l,min}}\cdot L} & -\frac{1}{s_{\text{l,min}}} \\ \frac{2}{s_{\text{l,min}}\cdot L} & \frac{2}{s_{\text{l,min}}\cdot L} & \frac{4}{s_{\text{l,min}}\cdot L} & -\frac{1}{s_{\text{l,min}}} \end{pmatrix} \tag{3}$$

To calculate the vertex, it is necessary to solve a system of equations based on a matrix in equation (3). The coordinates for an equation (2), are

$$C\ [C_1; C_2; C_3] = \left[\frac{L}{8}; \frac{L}{8}; \frac{L}{8}\right] \tag{4}$$

where L is the span of a simply supported beam.

This result was further verified using a parametric study in a spreadsheet to confirm the correctness of the calculation. Considering the variation of spacing in units of per cent of beam length, there are 19,600 possible combinations for 4 different spacings. This indicates that for a larger number of spacings, the number of combinations would be enormous. Therefore, calculating the ideal position for changing the centre-to-centre distance of shear studs using the extension matrix (3) is considerably easier. Using the matrix for five different spacings, the coordinates for changing the spacing equal to 1/10 can be obtained. In a similar way, it can be calculated that for six spacing, the ideal distances to change are by $L/12$, for seven $L/14$. This shows a dependence where eight spacings can obtain $L/16$, for nine $L/18$ etc.

However, this situation is only valid under ideal conditions where the axial distance of the shear studs can increase theoretically to infinity. In practice, it is limited by the design principles that specify the maximum allowable spacing. This equals to the lesser value of 6 × the height of the shear stud or 800 mm. Therefore, as in the previous research [9], the hypothesis was tested that the smallest number of studs can be achieved by finding the distance x' at which the maximum possible distance between the shear studs must be maintained and dividing the remaining section into equally sized parts as is shown in Fig. 2. The distance x' is found according to the equation

$$x' = \frac{1}{2}L - \frac{P_{\text{Rd}}\cdot n_{\text{r}}\cdot n\cdot I_{\text{i}}}{S_{\text{c}}\cdot s_{\text{l,max}}\cdot q} \tag{5}$$

where L is the span of a simply supported beam in mm, P_{Rd} is the design load-bearing capacity of a shear stud in N, n_{r} is the number of shear studs in the transverse direction, $n = E_{\text{a}} / E_{\text{c,eff}}$ is the modular ratio, I_{i} is the second moment of area of the ideal cross-section in mm^4, S_{c} is the first moment of the concrete slab in mm^3, $s_{\text{l,max}}$ is the maximum allowed centre-to-centre spacing of shear studs in mm and q is the value of the uniformly distributed load on the beam in N/mm.

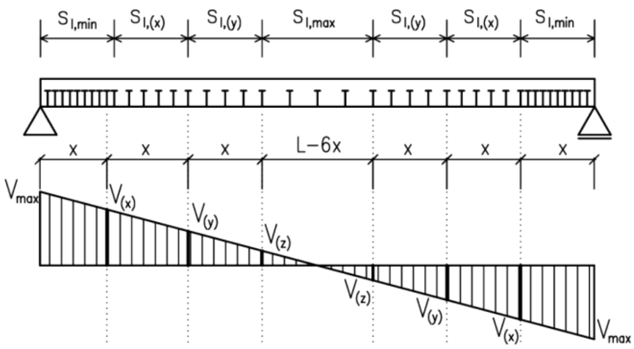

Fig. 2 A diagram of the shear stud distribution, where the maximum allowable centre-to-centre spacing of shear studs is applied along the entire length to which the limit of the design principles is relevant and the remaining edge parts are divided into three equal sections.

3 RESULTS

The parametric study was performed using a spreadsheet. A simply supported beam of 10 m in length loaded by a uniformly distributed load of 15 kN/m was used as the reference beam for the parametric study. The beam was assumed to be made of an 80 mm high concrete slab with an effective width of 2,200 mm made of concrete C25/30 and IPE 300 profile made of structural steel S235. Shear studs with the heads of strength of 4.8, 50 mm length and 16 mm shank diameters were used as coupling elements. The distance of sections *x*, *y* and *z* was varied in units of percentages, up to the total sum $x + y + z = 50$ % of the beam length. This created 19,600 configurations of different lengths of sections *x*, *y* and *z*. The number of coupling studs was calculated for all of them.

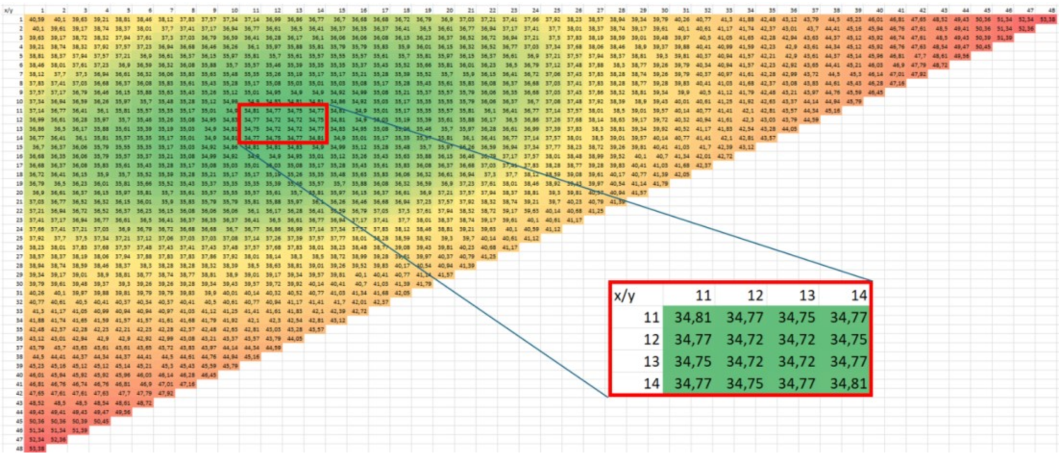

Fig. 3 Colour scale showing the number of shear studs for percentage values of *x*, *y* and *z* section lengths for ideal conditions without the influence of limitations from design principles.

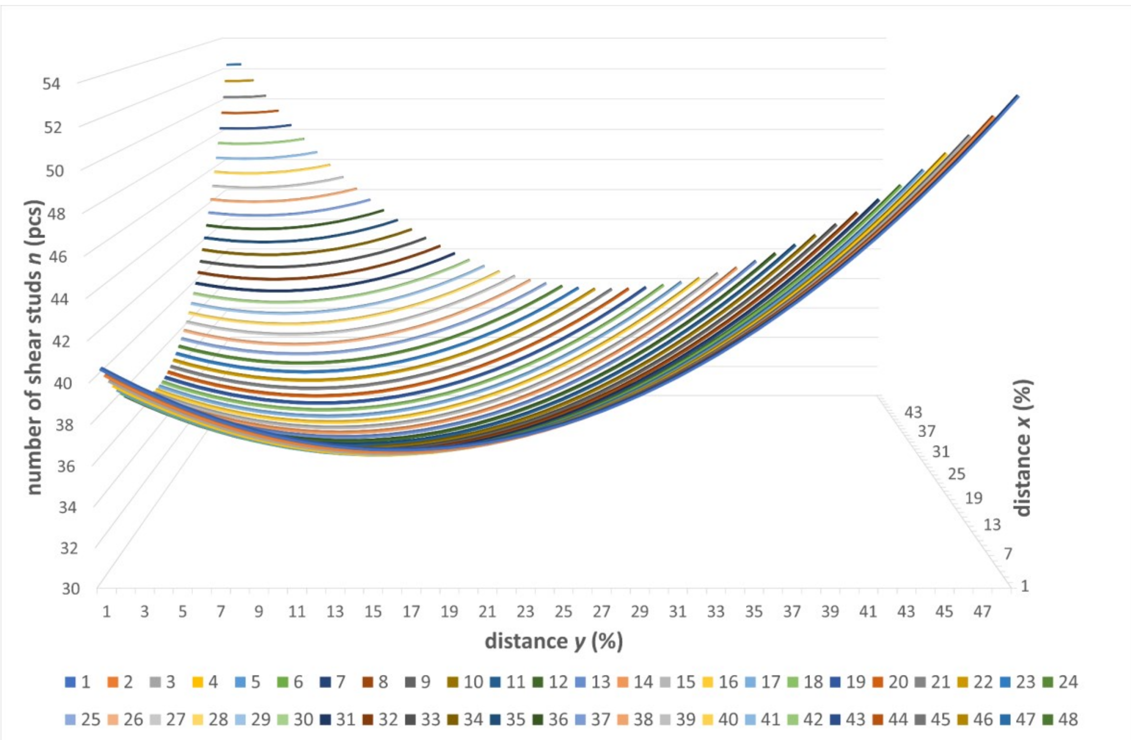

Fig. 4 Spatial chart of the dependence of the number of used shear studs on the percentage length of the *x*, *y* and *z* sections in which the change of spacing was made. This chart is for the case without restrictions of the design principles.

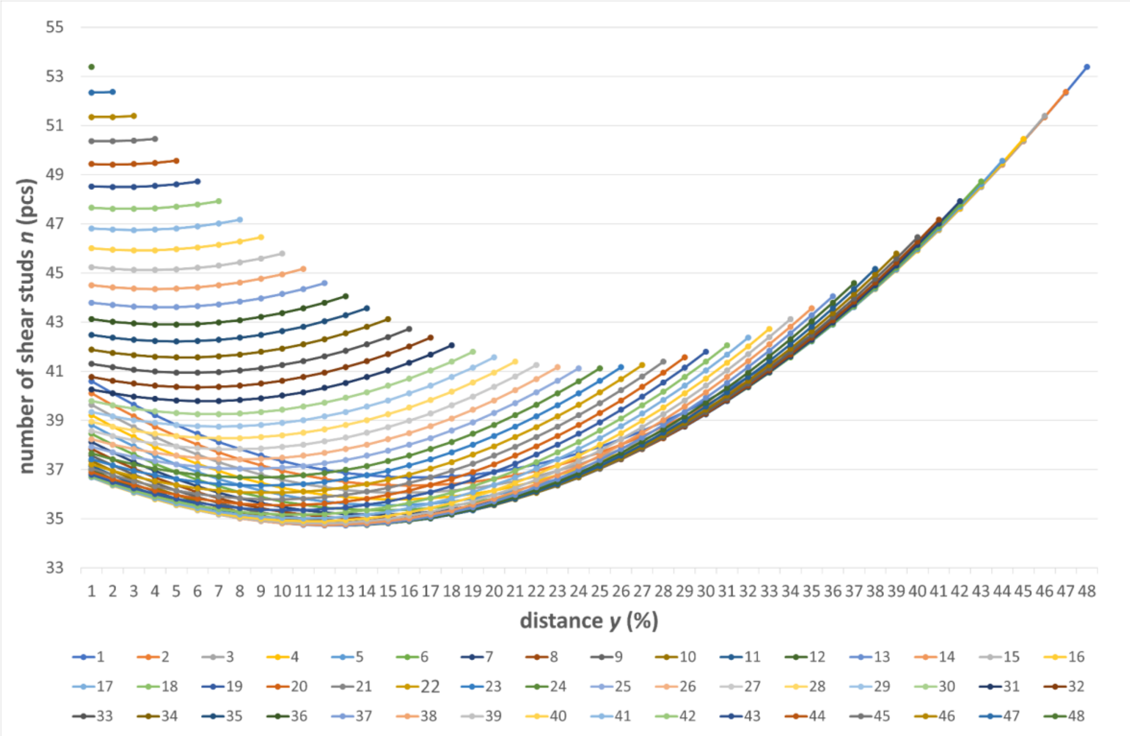

Fig. 5 A planar chart showing the dependence of the number of shear studs on the percentage increase in the length of section *y* for different percentage values of length *x* without limitation of the design principles. (The data is based on the table shown in Fig. 3.)

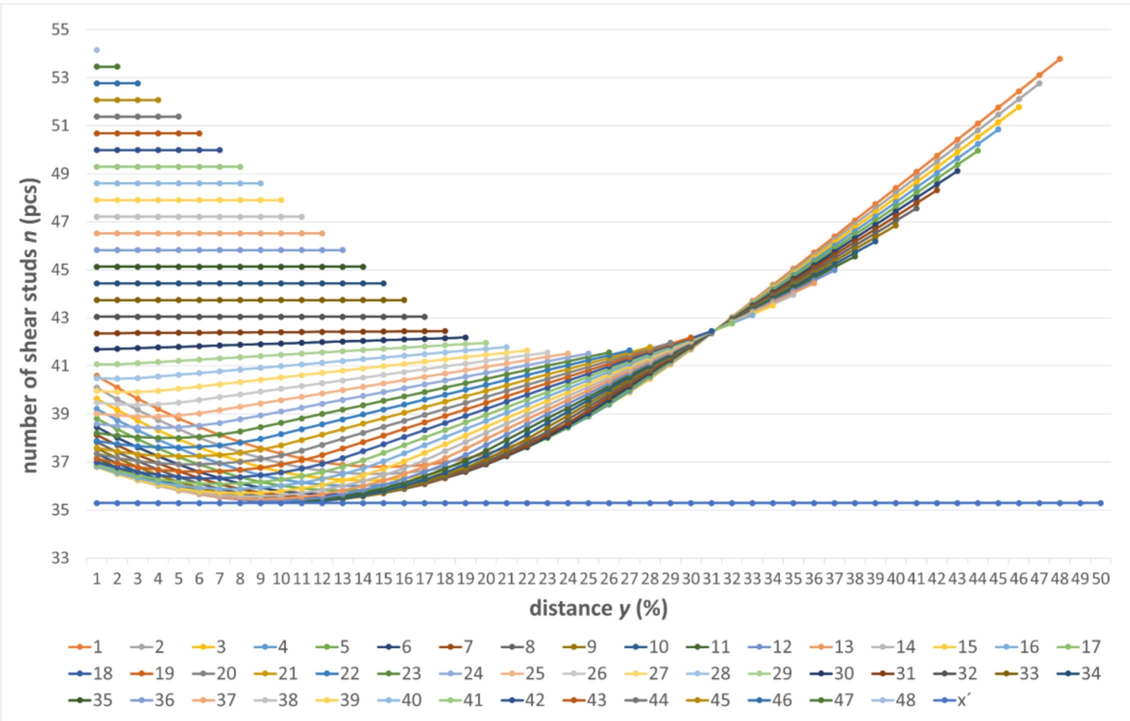

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Fig. 6 A planar chart showing the dependence of the number of shear studs on the percentage increase in the length of section *y* for different percentage values of length *x* including the limitation of design principles. The straight blue line shows the case of shear studs distribution according to Fig. 2.

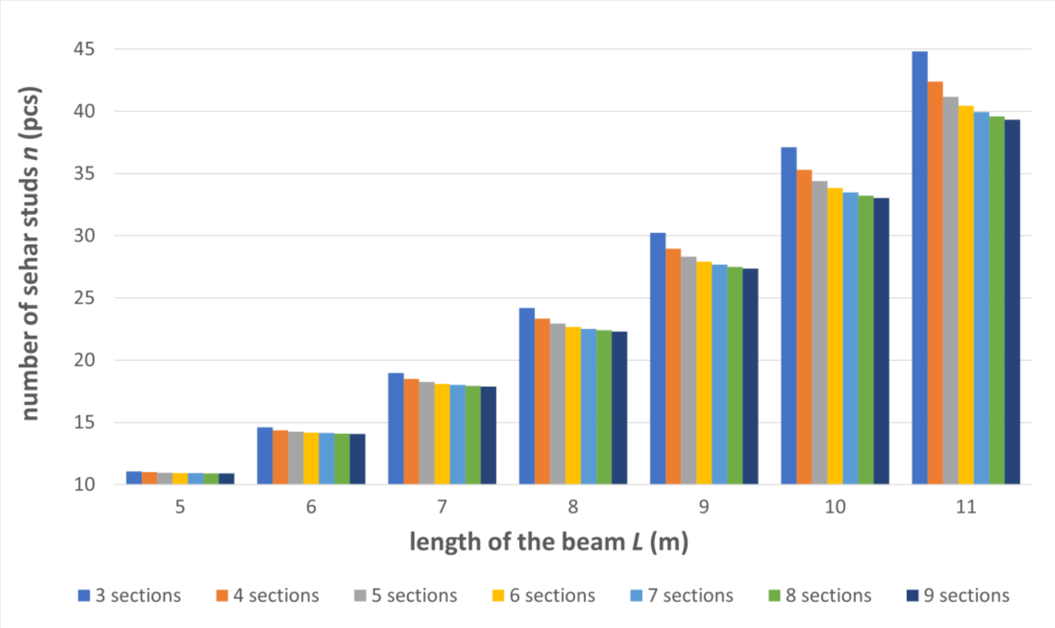

Fig. 7 Chart comparing the number of shear studs for different numbers of sections with different axial spacing of coupling elements for beams of different lengths.

4 DISCUSSION

The results of the parametric study show the number of coupling elements on the beam as a function of the percentage lengths of sections *x*, *y* and *z*. As mentioned earlier, there are 19,600 combinations of the lengths of the individual sections, up to a maximum of half the length of the beam. This is quite a large quantity of information, difficult to convert into a simple chart. An ideal representation of the point at which the minimum of coupling elements is reached would have to be made in space. The percentage lengths of each segment would correspond to three mutually perpendicular axes, and the corresponding number of studs would be written at their intersection. This would create a tetrahedron and somewhere within its volume would be the point where the minimum of shear studs is reached. Since this representation is complicated, it was simplified by breaking the tetrahedron into individual "levels". The data from the parametric study was arranged so that for each value of *x*, a separate table was created. The columns indicated the *y* position and the rows the *z* position. The corresponding values of the number of studs were listed in the table. Only one common table was created with columns for *y* and rows for *x* from these triangular tables. A minimum value of *n* was found for each column *y* from the sub-tables, and inserted into the common table. At the same time, the next table marked for which value of *z,* this minimum was reached.

Fig. 3 shows the table for a simply supported beam with a uniformly distributed load without limitations due to design principles given in EC4 [1]. Colour scale shows the number of shear studs for percentage values of *x*, *y* and *z* section lengths for ideal conditions without the influence of limitations from design principles. Green indicates the minimum number of studs and red the maximum. Each field of the table is filled with the minimum value of the number of shear studs for different values of length *z* corresponding to the given lengths *x* and *y*. On a beam where four different spacings of coupling elements are used, the minimum of the studs is reached at *x* and *y* distances between 12 and 13% of the beam length. It can be found from the corresponding table that this number of studs also corresponds to a *z*-value between 12 and 13 %. The results are shown in the chart in Fig. 4 for better illustration. Since a spatial chart can be harder to read, a planar chart was created from the already summarized values in the common table (see Fig. 5). It can be already clearly seen that the minimum of the coupling elements is reached for a *y*-value between 12 and 13 %, corresponding to an *x*-curve of 12 and 13%. It was found from the calculation of the matrix (3) that the coordinates of the point where the minimum of the shear studs is reached, should be equal to $x = y = z = 1/8$ (equation (4)). This corresponds to a value of 12.5 %. Thus, the parametric study confirmed the correctness of the relation (2) and the possibility of using the extension of the matrix (3) for more variables than the 3 presented in [10].

However, in practice, the limitations of the design principles must be taken into account. The maximum permissible spacing of shear studs is defined. If this restriction is accepted, the point x' on the beam is obtained from which the spacing of the coupling elements can not be further increased. This limitation causes the curve indicating the number of shear studs to become straight and the minimum number of studs to move closer to the support (as seen in Figure 6). As in the previous study, the hypothesis was considered whether, considering the limit of the design principles, there is a more suitable place on the beam to change the centre-to-centre spacing of shear studs than after 1/8 of the beams length. Consider the configuration of Fig. 2. when the point x' is found according to equation (5), from which towards the centre the maximum spacing $s_{l,max}$ must be used and the further division of the edge parts into equally sized sections. The number of studs from this configuration is shown in Fig. 6 by the blue straight line. As can be seen, this configuration results in shear stud numbers equal to the minimum values from the method described above. It can be seen that the best distribution using four different axial distances of the coupling elements is achieved with the layout shown in Fig. 2. The distance over which the limitations of the design principles apply is calculated using equation (5) and the maximum allowable axial spacing of the spikes $s_{l,max}$ is applied. The remaining parts are divided into the same sections $x = y = z$. Shear spacing of the studs $s_{l,min}$ corresponding to the maximal shear force is used on the edge section near the support and the other sections use the spacing corresponding to the force at the points of change of the axial spacing of the studs.

Since this configuration is suitable for beams with three or four different axial distances of the shear studs, it can be assumed that this is also applicable to beams with multiple sections. Fig. 7 shows a comparison of the number of studs for beams of lengths 5-11 m, using different numbers of sections per beam. The number of shear studs decreases for a higher number of sections. This difference is more noticeable for longer spans which are stressed by higher bending moments. However, the difference for higher numbers of sections is not significant and because of the necessary rounding, the amount of studs into whole numbers is almost negligible. More significant difference can only be observed between beams of three and four sections. There the difference is even a few units of shear studs. This implies that the use of 4 sections with different axial spacing of the coupling elements can still be favourable. A larger number of sections no longer offers a major benefit in a lower number of shear studs.

5 CONCLUSION

The parametric study confirmed the correctness of the derived relationships even for a larger number of sections with different axial distances of the studs. The number of coupling elements on a beam with 4 sections was compared with the proposed distribution of studs on the beam, where the maximum allowable spacing of studs was used on the section following the design principles and the remaining edge sections were divided into three equal-length sections. This configuration has proven to be the most suitable for achieving the fewest number of studs on the beam.

Finally, a parametric study was carried out with beams of a different numbers of sections designed according to the above-described configuration. It was shown that for a beam with 4 sections, the number of coupling elements can be further reduced by units of pieces according to the beam parameters, compared to a beam with two or three sections. A larger number of sections does not have a significant effect and therefore it is useless to design it.

This theoretical research will serve as a basis for further work.

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