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Analytical investigations to the specimen size effect on the shear resistance of the perfobond shear connector in the push-out test

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Abstract

Perfobond shear connectors (PSCs) are widely used in steel-concrete composite structures as an available alternative to the shear studs which have a limited shear resistance, and are prone to fatigue problems. The evaluation of the structural performance of PSC ribs is mainly obtained through a destructive test known as the push-out test (POT). However, the size of the specimen in the POT is varied significantly. The main objectives of this study are (i) to examine the effect of the POT specimen size on the predicted shear resistance of the PSCs by conducting numerous numerical analyses to the design parameters that affect the shear resistance obtained from POT test. The numerical investigations were conducted utilising several empirical shear resistance equations which are originally derived from the regression analysis of the POT results. These investigations were performed on Eurocode-4 (EC-4) and British Standard-5 (BS-5) POT specimens as the size of these specimens is varied significantly. Furthermore, (ii) to quantify the scale of the influence of the design parameters in the POT on the resulting shear resistance by conducting several sensitivity numerical analyses as the design parameters have variable effects on PSCs shear resistance. The results of this study suggest that the size of the POT specimen has a minor effect on the predicted shear resistance which might have the same effect on the actual shear resistance from the push-out test. In addition, the results of the sensitivity numerical analyses have shown that both the diameter of the holes and the rebars are the most influential factors on the shear resistance of the PSC, and the thickness of the connector has the least influence among the other design parameters, and the effect of the design parameters on the PSC shear resistance is varied according to the geometry of the connector. Further, a more efficient design for PSCs is presented by selecting large holes in a small number instead of small holes in a large number for the same cross-sectional area of the connector. This efficient design has the potential to increase the PSC shear resistance which directly affects the bending resistance and deflection of the composite beams that employ the perfobonds as a shear connector.

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Keywords: push-out test; perfobond; shear resistance; numerical investigation; sensitivity analysis

1 Introduction

The most popular shear device in the composite steel-concrete beams is the shear stud (Ahn, et al., 2010). However, the shear studs have limited shear resistance and prone to fatigue problems. The welded PSCs, which are perforated rectangular steel plates, have been used as an alternative for the shear studs due to their high resistance for both the shear stresses and fatigue problems (Su et al., 2016). Cho et al. (2012) illustrated several employments of the PSCs in the composite bridges industry. PSCs have been also used in the composite joints of hybrid bridges which employ the combination of steel girders and concrete girders (Xiao et al.,2016). Recently, the PSCs, are utilised to strengthen the steel pile embedded into the foundation which can assure a strong composite behaviour among the structural components at the pile cap (Kim et al.,2016).

Typically, the assessment of the structural performance of PSCs is carried out experimentally through the push-out tests. In the POT test, shown Fig. 1(a), two concrete slabs (blocks) are attached to I- steel section by means of the PSC under investigation. A direct shear force then applied to the steel section until the fracture of slabs and/or the shearing of connectors. The relative movement, i.e. the slip, in the direction of load between the steel section and the concrete slab is recorded to draw a load-slip curve which defines the characteristic behaviour of the shear connector such as the ductility and connector shear resistance.

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Different numerical expressions are available to estimate the shear resistance of the PSCs. These expressions have been mainly obtained from the regression analysis of POT results (Su et al., 2016). However, the size of the specimen in the push-out test is varied significantly among the researchers. Fig. 1(b,c) shows, for instance, several POT specimens used by different researchers. The variation of the size of the concrete blocks can be also seen in the codes of practices, i.e. BS-5 and EC-4 samples. The large variation in the size of slabs of the POTs is due to two main reasons. Firstly, the wide range of the geometrical configurations of PSCs, and secondly the aim to reduce the difference in the results of the PSC shear resistance obtained from the composite beams full-scale testing and POTs.

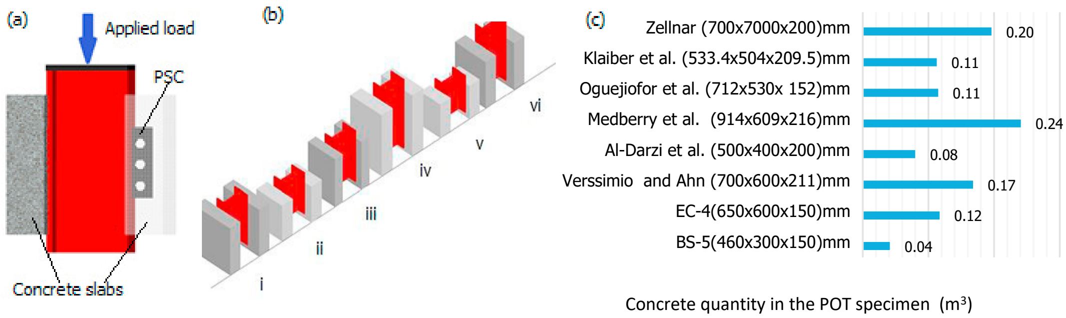

Fig. 1. (a) POT setup; (b) POT specimens utilised by (i) Zellnar (1987), (ii) Klaiber et al (1997), (iii) Oguejiofor et al. (1994), (iv) Medberry et al. (2002), (v) Al-Darzi et al., (2007b), (vi Verssimio et al. (2006) and Ahn et al. (2010); (c) the concrete q

This numerical study attempts firstly to examine the effect of size of the POT specimen on the predicted shear resistance of the PSCs obtained from several well-known numerical expressions, and secondly to quantify the scale of the influence of the design parameters in the POT on the resulting shear resistance as these parameters have variable effects on the PSC shear resistance.

2 Method of investigation

2.1 Theoretical assumptions

The numerical investigations involve the design of two POT samples according to the BS-5 & EC-4 specifications to represent the actual configurations of the push-out tests, see Fig. 2(a,b). The selection of the POT specimens according to these codes of practices was for several reasons. (i) the BS-5 sample is the smallest among all the POT samples which makes it an economical option especially in the large testing campaign, see Fig. 2(c). (ii) EC-4 sample has been used broadly among the researchers e.g. Cândido-Martin et al. (2010); Kang et al. (2014). (iii) the size of BS-5 POT sample is nearly one-third of the size of the EC-4, the dimensions of the concrete slab in the EC-4 POT specimen are (650×600×150) mm while in the BS-5 specimen are (460×300×150) mm. This large difference in the specimens' size enables a valid comparison to examine the size effect, i.e. if the size of the investigated samples is convergence then the predicted POTs results might also be convergence.

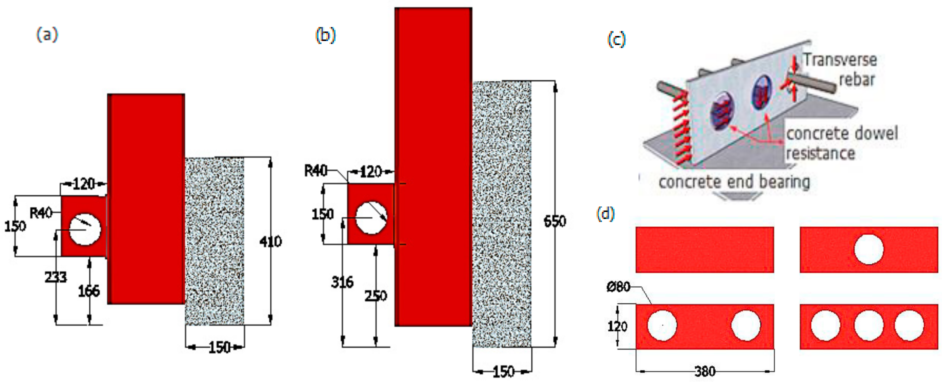

Fig. 2. (a) BS-5 specimen; (b) EC-4 specimen; (c) elements of the PSC shear resistance (Kang et al ,2014); (d) design parameters

These numerical investigations were preceding a testing campaign of a circular PSC of 150mm length, 120 height and 10 mm thickness, and has one 80mm-diameter hole. Thus, the PSC in these numerical investigations has the same designed dimensions of the actual connector, so that the outcomes of this paper can be used in the experimental campaign. The PSC, which is assumed to be located at the centre of the concrete slab, has one Ø 10 transverse rebar passing through hole. Fig. 2(a,b) shows the details of the PSC rib position, its reinforcement and the dimensions of both samples, i.e. BS-5 and EC-4, according to the design assumptions.

2.1.1 Numerical expressions for estimating the shear resistance

The PSC shear resistance consists mainly of three elements, namely the end bearing of the POT concrete slab, concrete dowel resistance and rebars' resistance, see Fig. 2(c). Five numerical equations were selected, shown in Table 1, to estimate the shear resistance of the two symmetrical PSCs in the BS-5 & EC-4 samples.

The selection of these equations was according to; the number of samples were used to derive these empirical expressions which covers a wide range of the design parameters; the consistency between the estimated shear resistance obtained from these expressions and the POTs results; the using of the finite element modelling besides the experimental, e.g. Al-Darzi et al. (2007b); the engineering concepts of deriving these equations, e.g. Medberry & Shahrooz (2002). The latters have used different concepts to obtain the elements of the PSC shear resistance from the other authors. Instead of the regression analysis to the POTs results, which was previously used by Oguejiofor & Hosain (1997), they adapted some of the reinforced concrete concept, such as the resistance of steel reinforcement in the shear-friction method of ACI (1997) to estimate the rebars' shear resistance (Medberry & Shahrooz, 2002). In fact, the other authors of the numerical expressions in this study have used the regression analysis to quantify the PSC shear resistance. Moreover, all the authors of these expressions have used different sizes of POT specimens, see Fig. 1(a,b).

In Table 1, the numerical expressions were re-written according to the three elements of the PSC shear resistance, i.e. end bearing, transverse rebar and concrete dowel, see Fig. 2(c).

Table 1. The numerical expressions used in this study.

$Q_{rib} = 4.50\, h_{rib} t_{rib} f_c' + 0.91\, A_{tr}\, f_y + 3.31 n\, D^2 \sqrt{f_c'}$	(1) (Oguejiofor et al., 1997)
$Q_{rib} = 0.747\, bh \sqrt{f_c'} + 0.413\, b_f\, L_c + 0.9\, A_{tr} f_y + 1.3\, n\, D^2 \sqrt{f_c'}$	(2) (Medberry et al., 2002)
$Q_{rib} = 4.04\, \frac{h_{rib}}{b}\, h_{rib} t_{rib} f_c' + 2.37\, nD^2 \sqrt{f_{ck}} + 0.16\, A_{cc} \sqrt{f_c'} + 31.85 \times 10^6 \left({A_{tr}}/{A_{cc}} \right)$	(3) (Veríssimo et al., 2006)
$Q_{rib} = 0.762\, h_{rib} t_{rib} f_c' + (255309 - 7.59 \times 10^{-4} A_{tr} f_y) + 3.97\, n\, D^2 \sqrt{f_c'}$	(4) (Al-Darzi et al., 2007b)
$Q_{rib} = 3.14\, h_{rib}\, t_{rib}\, f_c' + 1.21\, A_{tr} f_y + 2.98\, n\, D^2 \sqrt{f_c'}$	(5) (Ahn et al., 2010)

A modification was implemented into Eq. (2) by Medberry & Shahrooz (2002) to satisfy the proposed test conditions. The second term of Eq. (2), i.e. ($0.413\, b_f\, L_c$), which represents the steel flange contribution to the shear resistance, was not considered due to the intention to grease the flanges before the concrete casting.

In these equations, Q_{rib} is the estimated shear resistance of the PSC; f_c' is the concrete compressive strength; *D* is the diameter of the hole; *n* is the number of the holes; $h_{rib},\, t_{rib}$ are the height of connector and its thickness; A_{tr} is the cross-sectional area of transverse rebars; f_y is the yield strength of reinforcement; A_{cc} is the longitudinal slab area minus the connector area; *b* and *h* are the thickness of the concrete slab and the distance from the end of the rib to the bottom of the slab respectively.

3 Numerical investigations

The first stage in these investigations was to numerically examine the effect of the concrete compressive strength and the transverse rebars, and second stage to study the effect of rib geometry on the PSC shear resistance.

3.1 The effect of concrete compressive strength (f_c')

A range of concrete compressive strength was selected to study their effect on the predicted shear resistance of the same PSC. The rest of the test parameters were kept constant in both samples, i.e. the connector's configurations and rebars, i.e. one Ø10 rebar passes through the PSC hole. Fig. 3(a) shows that for the same f_c', only Medberry & Shahrooz (2002) estimation to the EC-4 sample is larger by 30% from BS-5 sample. The diffrence in the size of the POT samples hardly affects the estimated shear resistance obtained from the other equations, i.e. the same prediction for the shear resistance in both samples for a specific f_c'. In both samples, the change in f_c' from 20 N/mm² to 40 N/mm² causes about 50% increase in the PSC shear resistance; nevertheless, Al-Darzi et al.(2007b) prediction is less than 20%.

3.2 The effect of transverse reinforcement (A_{tr})

Five different types of the transverse steel reinforcement were investigated to examine their effect on the predicted shear resistance. The rebars were selected starting from 8 mm in diameter and ending with 16mm in diameter. These rebars were individually pass through the rib hole. The yield stress for the steel rebars was assumed to be equal to 500 N/mm^2. Also, the rest of the parameters were kept constant in both samples, i.e. the PSC geometrical parameters, and f_c' is equal to 25 MPa. All the numerical expressions have predicated the same shear resistance for the PSC in both samples for the same area of reinforcement, apart from Eq. (2), see Fig. 3(b). Eq. (2) suggests two different values of PSC shear resistance for each area of steel in the EC-4 and BS-5 sample. The predicted resistances in the EC-4 sample are higher than the BS-5 by a constant value, 50 kN, which is less, about 30kN, than the average of the predictions offered by Eqs. (1,3,5). According to Al-Darzi et al.(2007b), the transverse reinforcement has no effect on the PSC shear resistance in both samples, i.e. the shear resistance remains constant. Other researchers assume that the increase the rebars steel area by 50%, i.e. from 8mm to 10mm in diameter has limited influence on the shear resistance about 15 kN. Similarly, the change in diameter from 8mm to 14mm, which is twice the area of steel A_{tr}, increases the resistance in average by about 60 kN, less than 30%.

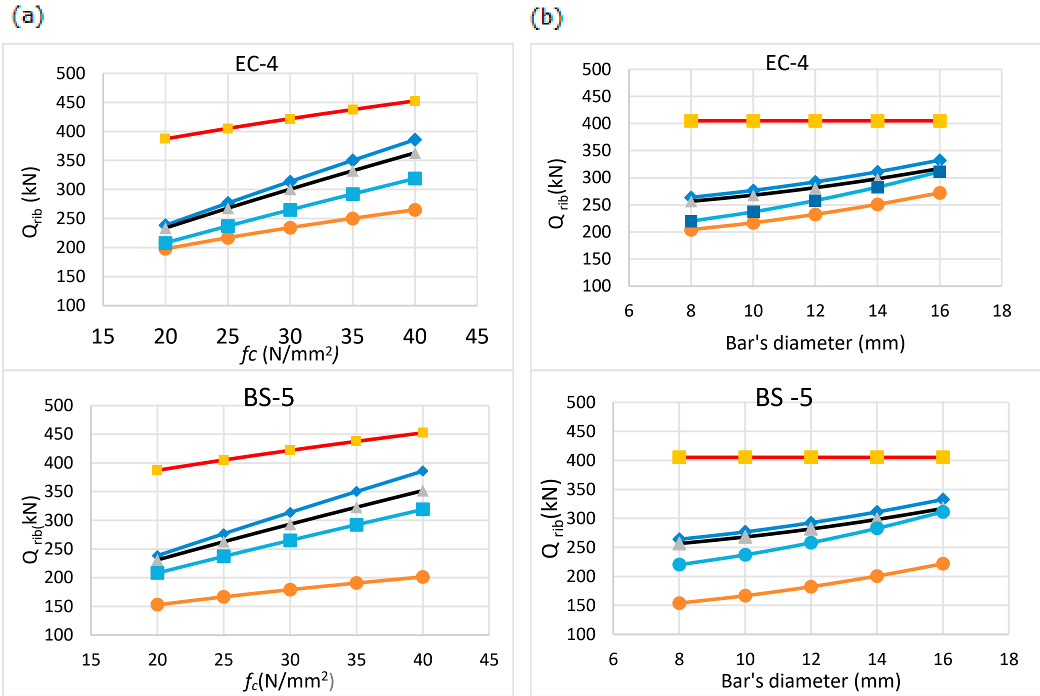

Fig. 3. The effect of (a) concrete compressive strength; (b) the transverse reinforcement.

3.3 *The effect of the geometry of the PSC*

Three parameters related to the PSC geometry, i.e. thickness, hole diameter and number of holes, were evaluated. In each step of the evaluation, one PSC configuration was changed while the other two parameters were kept constant. For instance, in the investigation of the effect of rib thickness both the diameter and the number of holes were constant, wherein the diameter is 80mm and the number of the holes is one. Similarly, the other test design parameters in both samples, i.e. A_{tr} and f_c', were also regarded as a constant value, 1- Ø10 and 25 MPa respectively, during the investigation of PSC *geometry*.

3.3.1 *The effect of the diameter of the hole*

As shown in Fig. 2(a), the PSC dimensions was 120x150 mm with one hole in the middle. Five different diameters were investigated starting from 40 to 80 mm. In both POT samples, the change in size of the hole has the same effect on the estimated PSC shear resistance; nevertheless, Eq. (2) estimation to the BS-5 sample, for the same diameter, is less than EC-4 sample by about 25%, in average. The changing the diameter from 40 to 80 mm increases the shear resistance by about 40% for both samples.

Al-Darzi et al. (2007b) estimation for the same change in diameter, who is the highest estimation, increases by less than 34%. Generally, in both samples, the increasing of the diameter by 100% enhances the PSC shear resistance by 40%.

3.3.2 *The effect of the PSC thickness*

Variety of PSC thicknesses were carefully chosen, as shown in Fig. 3(b), according to their popularity among the researchers and also in the construction industry to evaluate their effect on the shear resistance of the same PSC in both samples.

For the same value of thickness, the estimations of the five equations are nearly the same for both BS-5 and EC-4 POT samples except for Eq. (2) which is higher by 50 kN (about 30%) for the EC-4 sample than the BS-5 sample for the same thickness. Both Eq. (2) and Eq. (4) predict nearly a constant effect in both samples, i.e. the change in PSC thickness from 6mm to 14mm has zero or slight increase in the shear resistance; whereas, the other equations estimate the improve in the PSC shear resistance by about 30%.

3.3.3 *The effect of the number of the holes*

To study the effect of hole number, a longer PSC was chosen, 380 mm instead of 180mm, but with the same height and thickness, i.e. 120mm and 10mm respectively, see Fig. 3(c), Similar assumptions were assumed in this analysis also; the diameter of the hole is 80mm, the existence of 1-Ø10 as a transverse rebars through the centre of the each hole and concrete compressive strength is 25 MPa. As shown in Fig. 3(c), all the equations predict the same shear resistance in both samples for the same configuration excluding Veríssimo et al. (2006), i.e. their estimation is different for both samples as the final shear resistance is about 30 % higher in the BS-5 sample. Medberry & Shahrooz (2002) estimation is the lowest among the others but his prediction for the increment in resistance is the highest, the resistance of the PSC with three holes is more than 800% higher than the connector with no holes. For the same comparison, Al-Darzi et al.(2007b) predication is about 138%. Other researchers the estimation about (400 – 470) % in both samples.

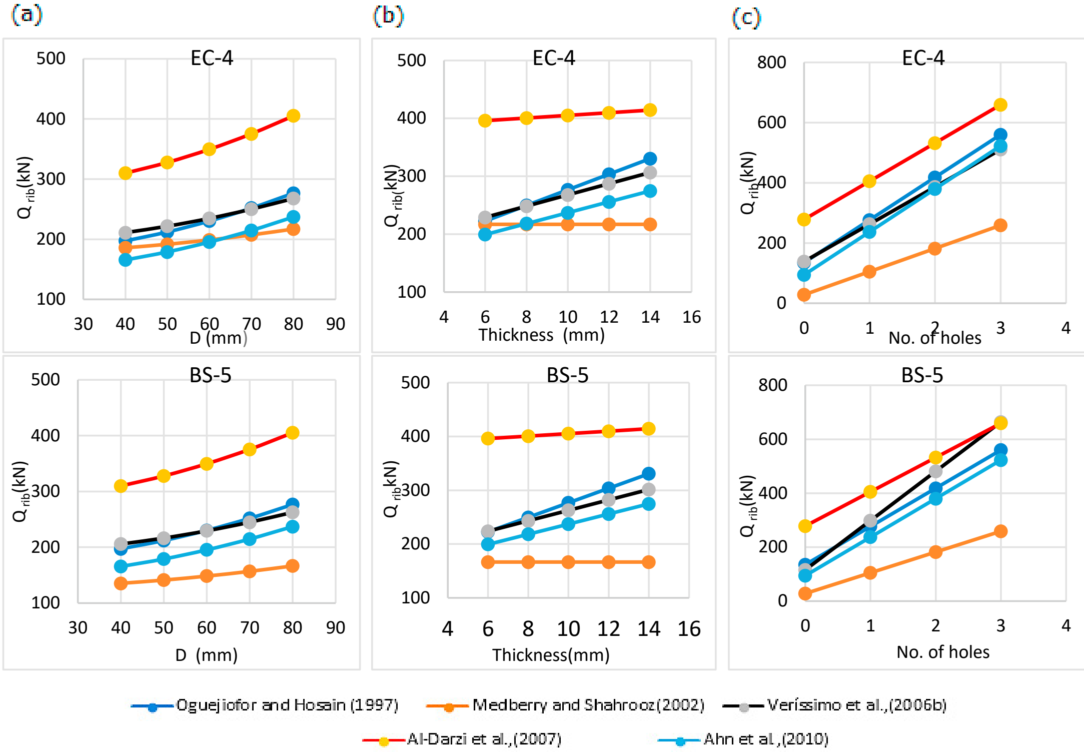

Fig. 4. The effect of (a) rib thickness; (b) the diameter of the hole;(c) the number of the hole.

4 Sensitivity numerical analyses

Various parameters affect the PSC shear resistance such as the rib geometry, concrete compressive strength and the transverse reinforcement; however, the effects of these parameters are considerably different. In order to quantify the effects of these different parameters on the shear resistance of PSCs several sensitivity numerical analyses were performed.

The sensitivity analyses have considered the same design parameters that were used earlier to study the POT specimen size effect, e.g. compressive strength of concrete was considered as 25 MPa, whilst the nominal yield strength of reinforcement was 550 MPa. All other parameters used in these analyses were the same as the actual parameters of the intended experimental campaign, i.e. the rib thickness is 10 mm; number of holes is one; the diameter of the hole is 80mm; the cross-sectional area of the transverse rebars is 230 mm^2. Appendix A shows an example for the sensitivity numerical analyses which were calculated to study the f_c' effect.

4.1 Concrete Compressive Strength

The influence of the variation in the compressive strength of concrete are shown Fig. 5(a). Oguejiofor and Hossain (1997) Eq. (1) and Ahn et al. (2010) Eq. (5) give the highest effect compared to the other equations, 0.53and 0.43 respectively. Verissimo et al. (2006) Eq. (3) and Al-Darzi et al. (2007b) Eq. (4) show less effect, less than 0.4. Medberry & Shahrooz (2002) Eq. (2) suggests the lowest effect which is about one-third the highest number.

4.2 The area of the transverse reinforcement (A_{tr})

Al-Darzi et al. (2007b) equation indicates that the increase in the cross-sectional area of the steel reinforcement has no contribution to the PSC shear resistance as the sensitivity ratio from this equation is equal to zero. Verissimo et al. (2006) and Medberry & Shahrooz (2002) demonstrate the highest effect for the A_{tr} on the shear resistance among the other equations, 0.45 and 0.4 respectively. The other two sets of the design equations suggest nearly half the sensitivity ratios of the pervious authors.

Fig. 4 (a) shows a considerable difference in the effect of the f_c' and A_{tr} between the researchers. These parameters, which are not related to the PSC geometry, apart from Verissimo et al. (2006), the other equations have shown a significant difference for both factors, whilst Verissimo et al. (2006) suggest almost a similar effect for f_c' and A_{tr}. In general, the concrete compressive strength has a significant effect according to Oguejiofor and Hossain (1997), Ahn et al. (2010) and Al-Darzi et al.(2007b) and nearly a convergence effect according to Verissimo et al. (2006). Indeed, Medberry & Shahrooz (2002) evaluation for the A_{tr} effect is more than double the f_c' effect.

4.3 Diameter of the hole

Fig. 4 (a,b) shows that all researchers have agreed that the diameter of PSC hole has the highest influence on the PSCs shear resistance. The hole diameter effect according to Verissimo et al. (2006), which is the lowest, is nearly twice the effect of f_c'.

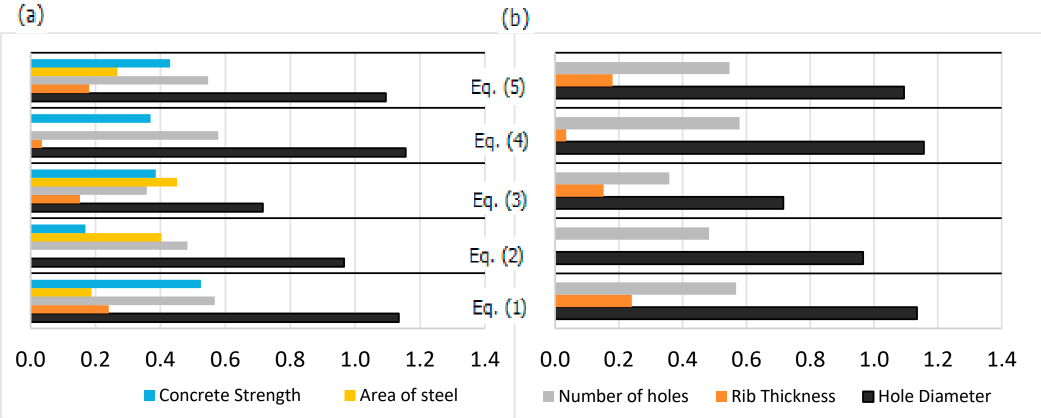

Fig. 5. The effect of (a) all the design parameters; (b) PSC geometry on the shear resistance.

4.4 Thickness of the rib

As shown in Fig. 5(b) the effect of the PSC thickness is divided into two main groups; a negligible effect according to Medberry & Shahrooz (2002) and Al-Darzi et al. (2007b), and a limited effect, about 20%, for the rest of the researchers. Indeed, the effect of the PSC thickness is the lowest among the other parameters.

4.5 Number of holes

All the numerical expressions indicate that the number of the holes has a comparatively large effect on the shear capacity for PSCs, see Fig. 5(a,b). Verissimo et al. (2006) provide a slightly lower percentage compared to other research, and this effect is less than effect of the cross-sectional area of reinforcement which is the second highest. The other four expressions have found this parameter provides a greater effect than the cross-sectional area of reinforcement.

According to the results of the sensitivity analyses, the effect of the number of the holes, which is the second highest effect, is nearly half the effect of hole diameter. This finding might be useful to optimise, in general, the PSC geometrical design with a particular benefit for the shallow PSCs. Thus, for the same plate, the use of large holes in a small number can provide more shear resistance compared to the same PSC using small holes in a large number as shown Fig. 7(a,b). The increase of the shear resistance has a direct effect on the degree of composite action between the slab and the girder which affects the structural performance of the composite beam such as the bending resistance and deflection. Ban & Bradford (2013) have confirmed numerically that the degree of the composite connection has a significant influence on the composite beam deflection.

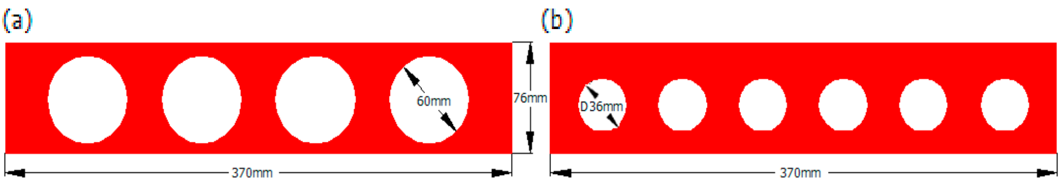

Fig. 6. More efficient design for the rib shear connector for the same plate.

5 Results and discussion

Although Medberry & Shahrooz (2002) and Al-Darzi et al. (2007b) empirical expressions, which have been used in this research and also by other researchers, used the POTs results to derive Eq. (2) and Eq. (4) a significant difference in the estimated shear resistance obtained from these two equations with the estimations offered by Eqs. (1,3,5). Eq. (2) estimation is the lowest among the other, and the reason might be because the authors have adapted the concepts of the reinforced concrete such as the shear-friction, as it was mentioned early, which are not completely suitable to estimate the POT result. Regarding Eq. (4) estimation, generally, by far higher than the other four estimations. Although the authors have used the regression analysis for the POTs results, which were obtained experimentally and numerically by FE method, the authors used the regression analysis with a constant value and not zero value for the resulting equation contrary to Eqs. (1,3,5) which have zero constant.

By comparing the results of the sensitivity analyses of this study with the result of Harvey (2016), who used different PSC geometry, a clear difference in the effect of the design parameter on the PSC shear strength between the two studies which indicates that the effect of the design parameters is varied according to the PSC geometry. For example, in Harvey (2016) the effect of the concrete strength according to Oguejiofor and Hossain (1997) is 0.58 while in this study is 0.53, the same case for the rebars' effect which is 0.15 while in this study is 0.19.

6 Conclusions

Several conclusions can be drawn from the previous numerical investigations:

The results of this study have shown that the size of the specimen has a minor effect on the predicted shear resistance obtained from four of five numerical expressions, which are derived originally from the regression analysis of the POT results. This minor effect might be the same on the shear resistance quantified from the push-out test as the numerical expressions that are used in this study were originally derived from different sizes of POT specimens. Nevertheless, only Medberry & Shahrooz (2002) estimation is varied according to the size of the POT specimen.

The sensitivity analyses are carried out to quantify the influence of the design parameters on the shear resistance of the PSCs. The results of this study have shown that the PSC geometry generally is more influential than the effect of the surrounding medium. i.e. the concrete and the rebars, and the f_c' might affect the shear resistance more than the A_{tr}; nevertheless, this effect is varied significantly among the five numerical expressions.

The effect of hole diameter is, the highest among all the design parameter, about twice the effect of number of the holes, which is the second highest effect. This finding might be useful to optimise the PSC geometrical design with particular benefit for the shallow PSC. According to the results of the sensitivity analyses, for the same plate, the use of large holes in a small number is more efficient from using small holes in a large number. Indeed, the effect of the design parameters on the PSC shear resistance is varied according to the PSC geometry.

The results of this study can be used to optimise the design of composite beams which employ the prefobond shear connectors starting from the geometrical design of the connectors and ending with the selection of the concrete compressive strength and the reinforcement steel to acquire a higher shear resistance between the concrete slab and the steel girder and thus reduce the slip between the two elements, i.e. slab and girder, which causes several difficulties such as reduction in the moment resistance and additional deflection for the composite beam.

Acknowledgements

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Appendix A. Example of the sensitivity numerical analyses

An example for the calculations of the sensitivity analyses is shown in Table I. This table illustrates the steps in which the effect of the concrete compressive strength on the PSC shear resistance has been calculated. Wherein;

$$Fixed\ Ratio\ (FR) = Design f_{ci}' \,/\, Q_{rib} \quad (i)$$

and the sensitivity ratio (S_i) is calculated from:

$$S_i = FR * ((f'_{c\,i+1} - f'_{c\,i-1}) / (Q_{rib\,i+1} - (Q_{rib\,i-1})) \quad (ii)$$

Table I. The sensitivity analyses of the f_c' effect

Eqs.	f'_c (Mpa)	21.875	22.5	23.125	23.75	24.375	25	25.625	26.25	26.875	27.5	28.125	F R	S_i	S_{i+1}	S_{i+2}	S_{i+3}	S_{i+4}	$S_{avg.}$
Eq.(1)		522.6	530.2	537.7	545.2	552.6	560.0	567.3	574.6	581.8	589.0	596.1	0.04	0.52	0.52	0.53	0.53	0.53	0.53
Eq.(2)		249.3	251.4	253.4	255.4	257.3	259.2	261.1	263.0	264.9	266.7	268.5	0.10	0.30	0.14	0.14	0.14	0.14	0.17
Eq.(3)	Q_{rib} (kN)	607.9	613.6	619.3	624.9	630.5	636.0	641.5	647.0	652.4	657.8	663.2	0.04	0.35	0.39	0.39	0.40	0.40	0.39
Eq.(4)		631.7	637.4	642.9	648.4	653.8	659.2	664.5	669.8	674.9	680.1	685.2	0.04	0.32	0.38	0.38	0.38	0.38	0.37
Eq.(5)		492.6	498.7	504.8	510.9	516.9	522.8	528.8	534.6	540.4	546.2	552.0	0.05	0.45	0.42	0.42	0.42	0.42	0.43

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