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NAJNOVIJE ISTRAŽIVANJE DUKTILNOSTI PERFORIRANIH MOŽDANIKA

Rezime:

Značajna primena “Perfobond” moždanika u spregnutim konstrukcijama od čelika i betona rezultirala je razvojem potpuno nove grupe spojnih sredstava, označenih kao perforirni moždanici. Geometrija perforiranih moždanika osim na nosivost značajno utiče i na duktilnost spojnog sredstva. Duktilnost moždanika koja direktno zavisi od geometrije konektora definiše ponašanje smičućeg spoja. Početni rezultati istraživanja duktilnosti perforiranih moždanika dobijeni su na osnovu numeričkih modela koji su kalibrisani rezultatima eksperimentalnih ispitivanja ovog tipa moždanika. U radu su dati rezultati napredne numeričke analize na osnovu kojih je prikazana veza između duktilnosti i geometrije moždanika.

Key words: perforirani moždanici, smičući spoj, duktilnost, numerička analiza

RECENT RESEARCH ON DUCTILITY OF PERFORATED SHEAR CONNCTORS

Summary:

Significant implementation of “Perfobond“ shear connectors in construction of composite steel-concrete structures resluted in development of entirely new type of shear connectors, denoted as perforated shear connectors. Except the shear resistance of this type of shear connector, the overall behaviour of shear connection is strongly influenced by shear connector geometry. Ductility of shear connector, which is strongly influenced by connector’s geometry, defines the behaviour of shear connection. The results of resent research on ductility of perforated shear connectors are obtained from numerical models which are calibrated with results of experimental investigation of this type of shear connector. The results of extensive numerical analysis were used for definition of direct relation between connector’s ductility and geometry and presented in this paper.

Key words: perforated shear connectors, shear connection, ductility, numerical analysis

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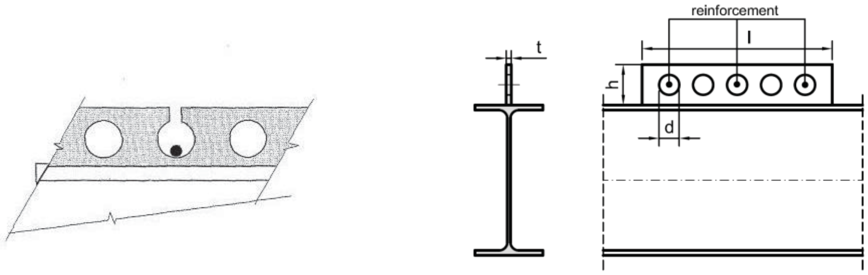
1. INTRODUCTION

The new type of shear connector which was developed in order to improve fatigue resistance of shear connectors in composite bridge construction was Perfobond Rib shear connector. This type of shear connector was developed in the 80s by German company Leonhardt, Andrea and Partners in designing the Third Caroni Bridge in Venezuela and shown in Figure 1a. The Perfobond Rib shear connector was developed as flat rectangular steel plate perforated with a series of holes. The connection between shear connector and top flange of steel beam is obtained by welding. The holes in the shear connector are spaced closely, and the diameter of the holes should be large enough to obtain enhancement of the concrete. Series of holes and embedded concrete volume form a series of concrete dowels which act in shear. Steel reinforcement may or may not be positioned in the Perfobond Rib holes, as shown in Figure 1b, which influence different behavior of shear connection.



a) Leonhardt's Perfobond Rib [1] *b) position of reinforcement in Perfobond*

Figure 1 – Perfobond shear connector

Development of a new group of shear connectors, which are currently denoted as perforated shear connectors, is the results of the massive application of this type of connector in different type of structures. Figure 2 presents perforated shear connectors with holes in two rows, puzzle connector and T-perfobont connectors.

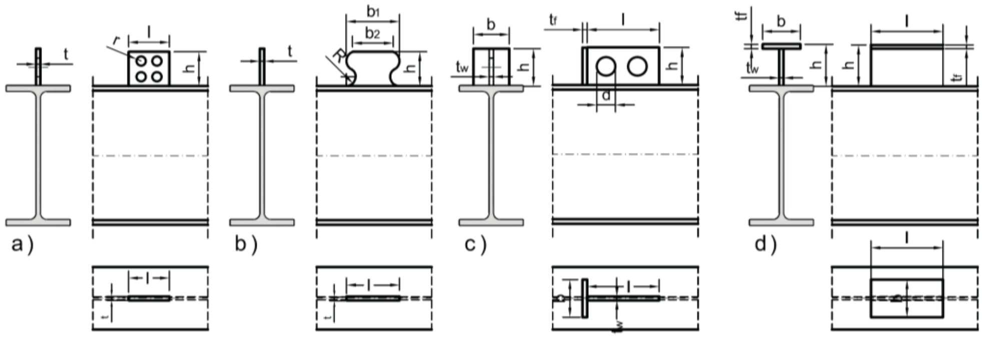


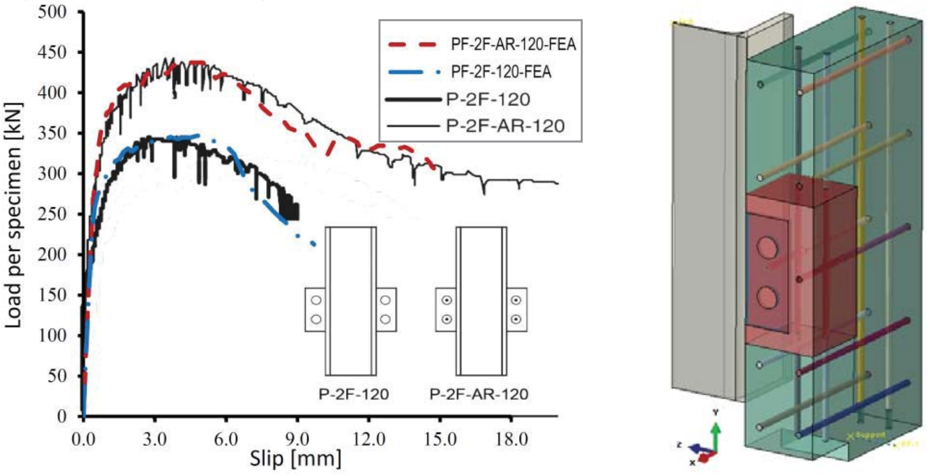
Figure 2 – Different types of perforated shear connectors

Development of different types of perforated shear connectors is followed with their experimental investigation through standard push-out tests according to EN 1994-1-1 [2]. Various geometry of perforated shear connectors shown in Figure 2, resulted in different sheer connection behaviour. Comparison of shear resistance and ductility of headed studs and perforated shear connectors' through numerical and experimental analysis is given by Spremić et al. [3]. Comparison is performed trough development of numerical models based on the experimental investigation of perforated shear connectors performed by Vianna et al. [4]. Investigation of perforated shear connectors given in [3] is extended and recent research on ductility of this type of shear connectors is presented in this paper.

2. NUMERICAL FE MODELS

Based on the experimental results, referred to Vianna et al. [4], the FE models was developed using the ABAQUS-Explicit dynamic solver [5] for quasi-static analysis. Non-uniform mass scaling was used. Quarter of the real experimentally investigated specimens for two types of perforated shear connectors was modelled using double vertical symmetry conditions, as shown in Figure 3. Calibration is performed for two push-out specimens, denoted as P-2F-120 (without reinforcement) and P-2F-AR-120 (with reinforcement), and results are presented by Spremić et al. [3].

For calibration of the material models of steel and concrete in ABAQUS [5] results from standard material tests presented in [4] were used. The isotropic plasticity model was used for the perforated shear connector for steel S355 and reinforcement with implementation of ductile damage and the shear damage models offered in ABAQUS [5].



a) load – slip curve after calibration

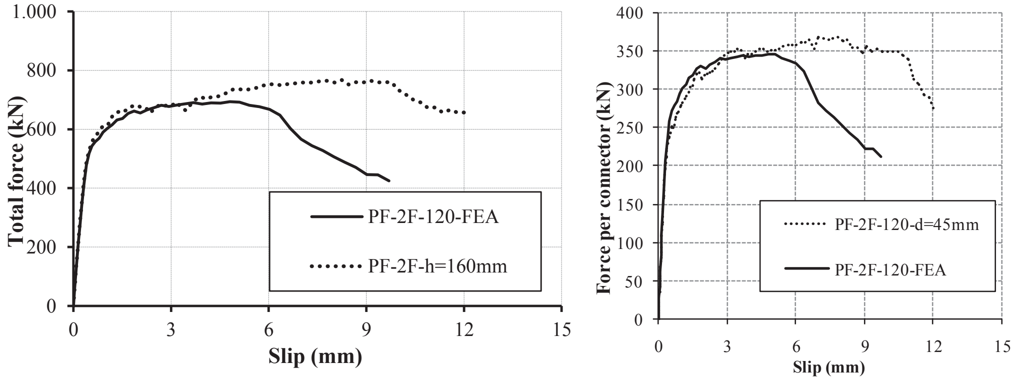
a) FE model [3]

Figure 3 – Calibration of numerical models

Concrete damage plasticity model was used for the concrete part of the specimen. The stress-strain curve was defined according to EN 1992-1-1 [6] up to the strain of ε_{cu1} = 3.5 ‰ with modulus of elasticity E_{cm} = 37000 N/mm^2 which correspondent to concrete C50/60 used in the experimental investigation [4]. For the strain $\varepsilon_c > 3.5$ ‰ the stress-strain curve for concrete is defined according to Pavlovic et al. [7]. The general contact interaction with friction was used for concrete and steel parts of numerical model. Displacement controlled failure loading, according to recommendations given in EN1994-1-1 [2] is applied in reference point at the top of the steel profile web.

3. PARAMETRIC STUDY

In parametric study presented in this paper three different parameters were analyzed in order to find indicative parameters for behavior of shear connection with perforated shear connectors. FE model validated upon push-out experiment for PF-2F-120 specimen presented in [3] is used for the parametric study. Specimen denoted with PF-2F-120-FEA is conducted with perforated shear connector with two holes with 35 mm diameter and 6 mm thickness. Total length and height of perforated shear connector is 180 mm and 76.2 mm, respectively. Through parametric study height of concrete slab, diameter of hole and thickness of shear connector is varied. Therefore, in further figures results of numerical model P-2F-120-FEA (without reinforcement), calibrated with the experimental results is used for development other numerical models with different perforated shear connector geometry. Numerical models with larger concrete slab depth, larger whole diameter and larger shear connector thickness are denoted with PF-2F-h=160mm, PF-2F-120-d=45mm and PF-2F-120-t=8mm, respectively.

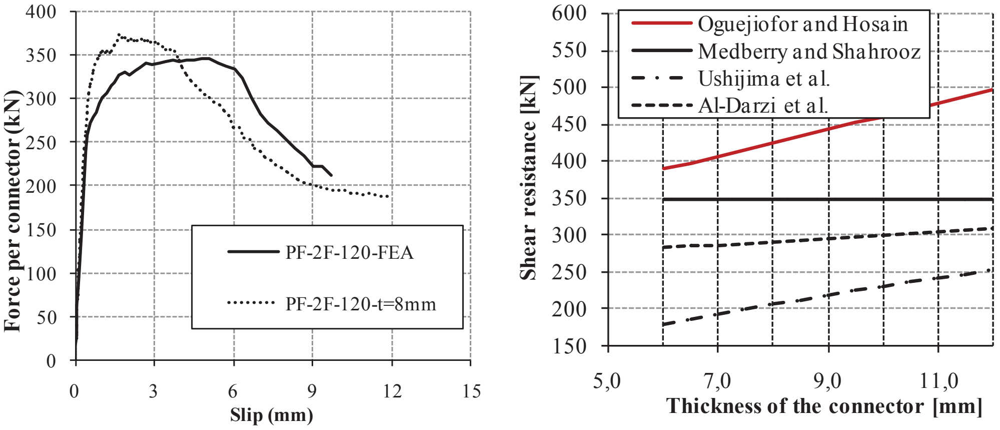


a) influence of slab depth *b) influence hole diamater*

Figure 4 – Influence of concrete slab depth and hole diameter

The concrete slab depth influence on ductility and resistance of perforated shear connector is analysed firstly, and presented in Figure 4a. Enlargement of concrete slab depth from 120 mm to 160 mm for specimen which is used for parametric analysis and explained before, influenced significantly on ductility which is increased for 60%. Ultimate shear force for whole specimen is enlarged from 693.7 kN for specimen with concrete slab depth of 120 mm to 767.0 kN for specimen with larger concrete slab depth. This represent enlargement of approximately 10 %. On the other side, slip to failure which represents slip for 90% of ultimate force on descending part of the force-slip curve, is enlarged from 6.6 mm to 10.7 mm.

The second parameter which was analysed in parametric study is hole diameter. The comparison is made for behaviour of two shear connections, one with perforated shear connector with 35 mm hole diameter (PF-2F-120-FEA) and the second one with 45 mm hole diameter (PF-2F-120-d=45 mm), both for 6.0 mm thickness of shear connector and 120 mm concrete depth. The results are given in Figure 4b. Enlargement of diameter hole for 10 mm resulted in small change of ultimate shear resistance, approximately 7 %, but in much larger change of ductility. Slip to failure is increased for approximately 60% and amounts 10.89 mm. Therefore, similar ductility increase is achieved with enlargement of hole diameter and concrete slab depth for the same thickness of shear connector.



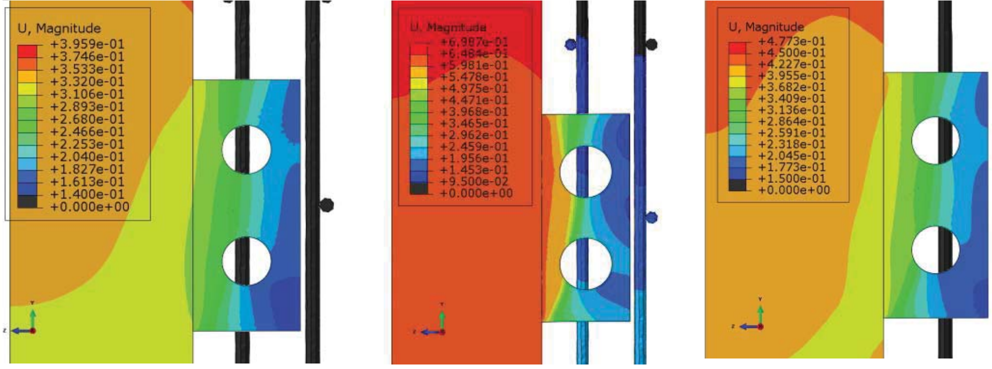
a) influence of connector thickness *b) predictive values of shear resistance*

Figure 5 – Influence of shear connector thickness

Further, through parametric study, influence of the shear connector thickness on shear connection behaviour is analysed for concrete slab depth of 120 mm. Behaviour of shear connection for two thicknesses, 6.0 and 8.0 mm are analysed and presented in Figure 5a. Enlargement of perforated shear connector thickness for 2 mm resulted in approximately 8% higher ultimate shear resistance. Also, slip to failure for thicker perforated shear connector is now 4.07 mm which is less than limit value given in EN1994-1-1 [2] for ductile shear connectors.

Different authors developed the predictive expressions for shear resistance of perforated shear connectors in function of different parameters, number of holes and their diameter and material properties of steel and concrete. These expressions are given in [4] and also presented in form of diagrams in Figure 5b. As shown in Figure 3 and Figure 5, for ultimate shear resistance obtained from experimentally investigated specimen PF-2F-120 and it's numerical model, the closest prediction is achieved with expression according to Medberry and Shahrooz [4]. Also, according to this expression, ultimate shear resistance is not influenced by thickness of shear connector. Moreover, ultimate shear resistance obtained from numerical analysis for thickness of 8 mm does not show close agreement with any of predictive values given in Figure 5b. Therefore, further development of predictive expressions for ultimate shear resistance of perforated shear connectors should include experimental investigation, but also extensive parametric study based on numerical FE models.

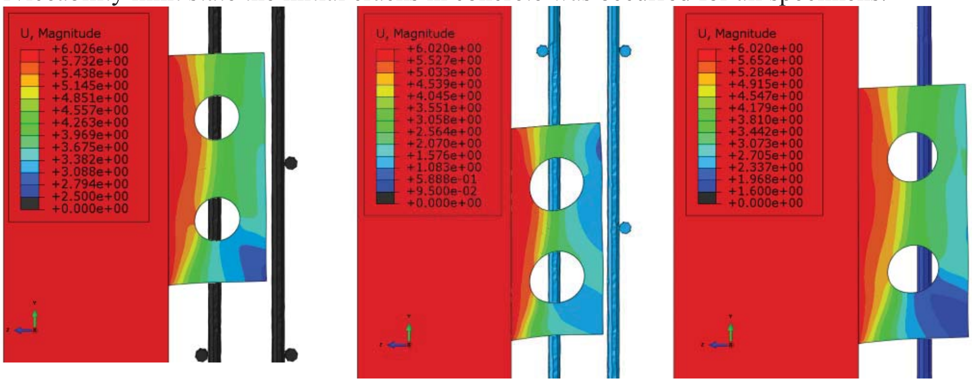
According to EN 1994-1-1 [4], shear connectors should be classified as ductile if the slip to failure is larger than 6.0 mm. Slip in shear connection is the effect of plastic deformation of the studs' shank. The compassion of perforated shear connectors' deformation, obtained from parametric study is given in Figure 6 and Figure 7. Also, the results of FE analysis of perforated connector's ductility are presented in Table 1 and Table 2. Deformation of connectors is calculated as the difference between the displacements in force direction of the top of the connectors and the connector's root.



a) PF-2F-120-FEA *b) PF-2F-120-d=45mm* *c) PF-2F-h=160mm*

Figure 6 – Deformation of perforated shear connectors at the shear load correspondent to SLS

Figure 6 presents the comparison of deformation of different types of perforated shear connectors at the load which represent approximately 70% of ultimate shear force, which can be considered as loading level corresponding to serviceability limit state. The same comparison for 6.0 mm slip is given in Figure 7. Even at the shear load value which corresponds to serviceability limit state the initial cracks in concrete was occurred for all specimens.



a) PF-2F-120-FEA *b) PF-2F-120-d=45mm* *c) PF-2F-h=160mm*

Figure 7 – Deformation of perforated shear connectors at the 6.0 mm slip

According to values presented in Table 1 deformation of perforated shear connector obtain similar values for two specimens PF-2F-120-FEA and PF-2F-h=160mm, and amounts 3.00 and 3.21 mm, respectively for shear load correspondent to SLS. This slip is the result of the connector deformation and has the similar values considering that the same perforated connector is used for both specimens, and only the concrete slab depth is changed. Another part of total slip of 6.00 mm is the result of the concrete failure. As shown previously, total slip to failure of whole specimen is increased for 60 % as a result of concrete slab height enlargement. Results for 96% of ultimate shear force for the same two specimens are given in Table 2. Higher concrete slab resulted in higher deformation of perforated shear connector which is now larger than 6 mm.

Table 1 –Deformation of perforated connector

Specimen	**slip at 70% ULS shear load**			**6.0 mm slip**		
	$U2_{root}$ [mm]	$U2_{top}$ [mm]	$U2_{top}-U2_{root}$ [mm]	$U2_{root}$ [mm]	$U2_{top}$ [mm]	$U2_{top}-U2_{root}$ [mm]
PF-2F-120-FEA	0.33	0.16	0.14	6.00	3.00	3.00
PF-2F-120-d=45 mm	0.38	0.12	0.26	6.00	1.50	4.50
PF-2F-h=160mm	0.39	0.16	0.23	6.00	2.79	3.21

Table 2 –Deformation of perforated connector at 96% ULS shear load

Specimen	**slip at 96% ULS shear load**		
	$U2_{root}$ [mm]	$U2_{top}$ [mm]	$U2_{top}-U2_{root}$ [mm]
PF-2F-120-FEA	8.00	4.50	3.50
PF-2F-h=160mm	9.99	3.50	6.49

Enlargement of hole diameter form 35 mm to 45 mm, resulted in significantly enlargement of connector deformation. Deformation of connector with larger hole diameter (specimen PF-2F-120-d=45 mm) is enlarged for 50 % approximately, but also limited to 4.5 mm, as shown in Table 1. Therefore, analysed perforated shear connector cannot be classified as ductile, considering that deformation of connector obtained through FE analysis is significantly influenced by connector geometry and specimens layout.

4. CONCLUSION

From the parametric study presented in this paper, following conclusions can be drawn:

- Behavior of shear connection with perforated shear connectors is in direct relation with connector’s geometry and depth of the slab. Different properties of perforated shear connectors, such as thickness or diameter hole can significantly influence the ultimate shear resistance and ductility.
- Initial cracks in concrete were occurred for all specimens even at the shear load value which corresponds to serviceability limit state. Failure of concrete is leading failure mode. Shear resistance of connection is in direct relation with shear bearing resistance of concrete slab.

- Thickness of connector has influence to shear resistance and ductility of connection. Higher shear resistance of this type of connector leads to lover slip value at ultimate shear load.
- Ductility of connection can be significantly improved adopting the perforated connector with larger diameter of hole.
- Connector with approximately 30% larger diameter of hole, 45 mm hole instead 35 mm hole, has similar shear resistance and 50% larger value of connector deformation.
- Higher concrete slab resulted in larger deformation of shear connector at loads which represent 96% of ultimate shear force and contributes to the larger ductility od shear connection.
- Considering obtained slip to failure for the analysed specimens with perforated shear connectors and their deformation, approximately 4.5 mm slip is the result of the connector deformation and another part is the result of the concrete failure. Therefore, it can be concluded that for certain specimen's layout, or even for different material properties of the concrete, this type of shear connector cannot be considered as ductile.

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