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Analysis of bolted ultra-high performance concrete joints

Análisis de conexiones con pernos en hormigones de ultra-alto desempeño

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Abstract

Ultra-high performance concrete (UHPC) is a composite material which has a remarkable self-compacting ability and high-compressive strength. Currently, UHPC precast construction is considered as an interesting option to take into account for civil engineering projects, in order to make use of its exceptional material properties. Discovering a practical and reliable method of connecting UHPC elements with fasteners has been recognized as a crucial factor in future construction projects. In this paper, the stress concentrations in an UHPC joint to predict brittle failure modes is investigated. Experimental results are compared with an analytical solution, which estimates the stress concentrations using the elastic properties of the anisotropic material and the geometry of the joint. The impact of the end and edge distances and elastic properties on the development of failure is presented for a bolted UHPC joint. The analytical solution proposed here that is based on closed-form equations, can be used to evaluate stress concentrations. Laboratory results on UHPC joints with bolts agree well with the model predictions. A theoretical analytical model for mechanically fastened precast concrete joints is, without a doubt, the reference for any experimental or numerical study of bolted UHPC joints.

Keywords: Analytical modelling; End distances; Stress concentrations; Concrete; Joints; Model predictions; Elastic properties.

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Resumen

El hormigón de ultra-alto desempeño (UHPC) es un material compuesto con una notable capacidad de autocompactación y una alta resistencia a la compresión. Actualmente, la construcción de prefabricados en UHPC, debido a sus propiedades excepcionales, es considerada como una opción interesante en los proyectos de ingeniería civil. El desarrollo de métodos prácticos y confiables para el diseño de conexiones con pernos de elementos en UHPC ha sido considerado como un factor crucial en futuros proyectos de construcción. En este artículo, se estudian las concentraciones de tensión y los modos de falla frágiles en conexiones con pernos de paneles UHPC. Los resultados experimentales son comparados con una solución analítica que estima las concentraciones de tensión usando las propiedades elásticas de los materiales anisotrópicos y la geometría de las conexiones. Se analizan la influencia de la distancia al borde y de las propiedades elásticas de las placas UHPC en el desarrollo de fallas en conexiones con pernos. La solución analítica propuesta en esta investigación considera ecuaciones de forma cerrada que pueden ser usadas para evaluar las concentraciones de tensión en la conexión. Los resultados de laboratorio en conexiones con pernos de paneles UHPC se ajustan a las predicciones del modelo analítico. Un modelo analítico teórico es sin duda un precursor para cualquier estudio experimental o numérico de conexiones con pernos de elementos de hormigón de ultra-alto desempeño.

Palabras clave: Modelo analítico; Distancias a los bordes; Concentraciones de tensión; Hormigón, Conexiones; Modelo de predicción; Propiedades elásticas.

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INTRODUCTION

Ultra-high performance concrete (UHPC) is a material with outstanding durability, a high-compressive strength, a sustained post-cracking tensile strength and notable self-compacting capacity. UHPC elements exhibit compressive and tensile properties higher of those from conventional and fiber-reinforced concretes. Currently, UHPC precast construction is regarded as an interesting alternative to be considered in civil engineering projects to take advantage of its exceptional material properties. Discovering a practical and reliable method of connecting ultra-high performance concrete precast elements with fasteners has been recognized as a critical factor in future construction projects (Maya et al. [1]).

Analytical, numerical and experimental methods have been used to investigate dowelled joints in anisotropic plates [2-11].

Echavarría and Salenikovich [12], presented an analytical model to calculate the stresses around a hole in a bolted joint and to predict failures in timber bolted connections. Timber bolted joints loaded parallel to grain were tested. Experimental results agreed well with theoretical predictions.

In Hammoud and Naaman [13], experimental work was carried out in order to study the behavior of ferrocement bolted shear joints. The type, number, and orientation of mesh layers, along with end distance and hole diameter were studied. Equations were developed to predict the net tension, cleavage, and bearing failure loads.

Maya et al. [1], have studied UHPC precast elements. The behavior of precast elements connected using short reinforcement splice lengths was analyzed. This configuration reduced the in-situ work.

Mansur et al. [14], have described an experimental investigation on ferrocement bolted joints. Laboratory tests have shown that the mode of failure of a moment joint depends on whether the applied moment is in the opening or closing mode.

Kwon et al. [15], have experimentally investigated the joint strength of bolted UHPC elements. The width, the thickness, and the distance from the center of the hole to the edge of the joint were considered. Results showed that the joint strength does not increase when the size and thickness of the joint augment.

Unfortunately, the research in bolted UHPC joints is so far insufficient (Camacho et al [16]). This lack of studies has delayed the development of an analytical design criteria.

The objective of this paper is to experimentally validate, in an UHPC joint, the analytical method, presented initially by Echavarría [17] capable of determining the stress distribution around a pin-loaded hole to predict brittle failure modes.

1. DEVELOPMENT OF BASIC EQUATIONS

The stress concentrations in an elastically orthotropic plate are examined for a joint loaded frictionless along the edge of the hole by an infinitely rigid pin (see Fig. 1 and Fig. 2). The loading force F is of magnitude pdt. Where d is the diameter of the hole, p is the bearing stress, and t is the unit thickness of the plate.

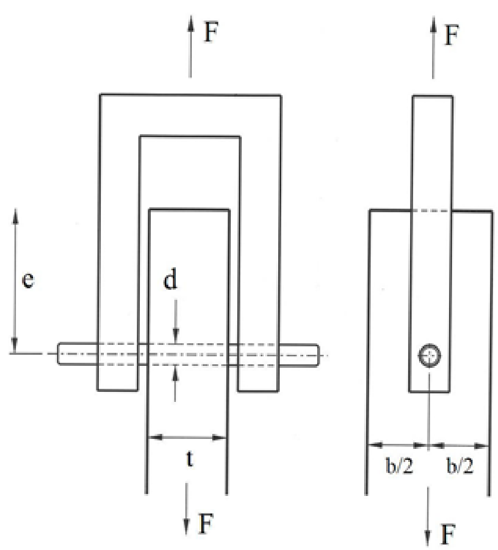

Figure 1. Joint geometry.

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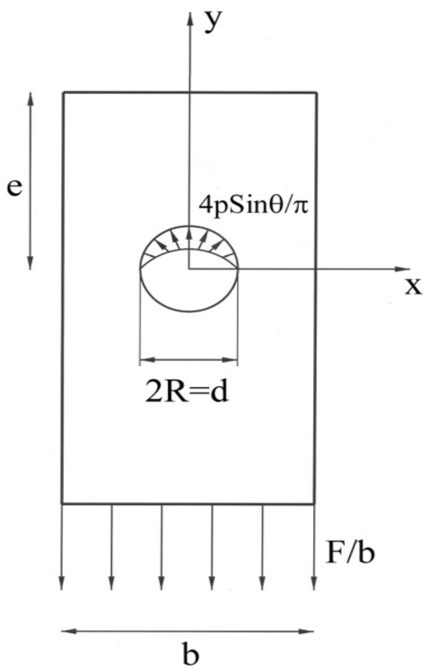

Figure 2. Joint under a sinusoidal distribution of load.

In general, the boundary conditions are used to calculate the stress functions. The stresses for the joint under consideration are summarized below.

The stresses at ($x = 0$, $y = d/2$) are calculated in this way:

$$\sigma_{x,max} = \left\{ \frac{(4+\pi)Fn\omega}{2R\pi^2} \right\} - \left(\frac{Fk}{2b} + \frac{3Fk}{2R\pi} \right) - \frac{\upsilon_{xy}F}{2R\pi} \quad (1)$$

$$\sigma_y = -\left(\frac{2F}{R\pi} \right) \quad (2)$$

$$\tau_{xy} = 0 \quad (3)$$

At ($x = d/2$, $y = 0$) , the stresses are:

$$\sigma_x = 0 \quad (4)$$

$$\sigma_{y,max} = \left(\frac{F}{2b} + \frac{2F}{R\pi^2} \right) \frac{n}{k} + \frac{F}{2b} \quad (5)$$

$$\tau_{xy} = 0 \quad (6)$$

where,

$$\omega = \frac{1 - Sin\,\alpha}{Cos\,\alpha} \quad (7)$$

$$\alpha = \frac{\pi}{5} \left\{ \frac{e-2d}{d} \right\} - \frac{\pi}{30} \left\{ \frac{e-2d}{d} \right\}^2 \qquad 2d \leq e \leq 5d \quad (8)$$

$$\alpha = \frac{3\pi}{10} + \frac{\pi}{45} \left\{ \frac{e-5d}{d} \right\} \qquad 5d \leq e \leq 14d \quad (9)$$

$$\upsilon_{xy} = \upsilon_{yx} \frac{E_x}{E_y} \quad (10)$$

$$k = \sqrt{\frac{E_x}{E_y}} \quad (11)$$

$$n = \left\{ 2 \left(\sqrt{\frac{E_x}{E_y}} - \upsilon_{xy} \right) + \frac{E_x}{G_{xy}} \right\}^{1/2} \quad (12)$$

where,

b	width of plate
e	end distance
E_x and E_y	orthogonal and longitudinal Young's moduli of elasticity
F	resultant force, predicted failure load
G_{xy}	shearing modulus of elasticity
R	radius of the hole
ν_{yx}	coefficient of Poisson
σ_x and σ_y	orthogonal stress and longitudinal stress
$\sigma_{x,max}$	highest orthogonal stress

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$\sigma_{y,max}$ highest longitudinal stress
τ_{xy} shear stress

Stress concentrations calculated with this analytical method are identical with those of the fundamental method found in De Jong [18] and Bickley [19]. The accuracy of De Jong's solution falls off in view of the excessive number of calculations. On the other hand, Bickley's solution considers only infinite isotropic plates.

2. PREDICTING BRITTLE FAILURES OF A BOLTED ULTRA-HIGH PERFORMANCE CONCRETE JOINT

There are four common failure modes in bolted joints, namely tension, shear-out, bearing, and cleavage. Unfortunately, brittle failures in UHPC bolted joints with inadequate end and edge distances and fastener spacing occur predominantly due to tension. In this study, the width of plate (*b/d* ratio) and the end distance (*e/d* ratio) were considered. Table 2 and Table 3 show the stress-concentration factors $\sigma_{x,max}$ and $\sigma_{y,max}$ (normalized by the average bearing stress *p)* assuming the elastic properties listed in Table 1 of a UHPC element of a unit thickness *t* and width *b*. For clarity, the tensile stresses are reported as positive.

- This analytical solution indicates that the reduction of the *b/d* ratio will increase the $\sigma_{y,max}$ and, simultaneously, will cause a reduction in the $\sigma_{x,max}$.
- Clearly $\sigma_{y,max}$ will increase if *b/d* decreases. When *b/d* is small, $\sigma_{y,max}$ generates a pure tension failure in UHPC joints because of their low ultimate longitudinal tensile strength.
- $\sigma_{x,max}$ will cause splitting in materials with a low ultimate orthogonal tensile strength (i.e. wood joints).
- The highest longitudinal compressive stress (Equation 2) is independent of *e/d* and *b/d* and can result in the bearing failure of the joint.

Considering a brittle performance of UHPC in tension and the maximum stress criteria, the joint will break predominantly when the highest longitudinal tensile stress $\sigma_{y,max}$ reaches the corresponding strength value.

Table 1 Material properties of UHPC

E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	ν_{yx}	Tensile strength (MPa)
45	45	18.75	0.20	10

Table 2 Orthogonal stress concentration ($\sigma_{x,max} / p$)

e/d	Equation (1)			
	$b = \infty$	$b = 16d$	$b = 8d$	$b = 4d$
2	0.43	0.40	0.37	0.30
4	-0.46	-0.49	-0.53	-0.59
8	-0.71	-0.74	-0.77	-0.84
16	-1.02	-1.05	-1.08	-1.14

Table 3 Longitudinal stress concentration ($\sigma_{y,max} / p$)

e/d	Equation (5)			
	$b = \infty$	$b = 16d$	$b = 8d$	$b = 4d$
2, 4, 8, 16	0.81	0.90	1.00	1.19

3. EXPERIMENTAL VERIFICATION

Laboratory tests on ultra-high performance fiber reinforced concrete (UHPFRC) joints with the geometry shown in Fig. 1 were conducted to validate the maximum stress concentrations predicted by the model.

An in-house developed UHPFRC mix made with CEM HE ASTM C1157 type cement, silica fume, and a superplasticizer was used for the experiments. The UHPFRC specimens used straight non-deformed steel fibers that were 13 mm long and had a 0.2 mm diameter. These fibers were included in the mix at a concentration of 2% by volume.

Static load applied in tension using a universal testing machine was used. The displacement-control rate of loading was set to reach failure in 5 to 15 minutes. UHPFRC elements for the joints were cut from 1 by 1-m panels. In addition, the elastic properties of UHPFRC

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panels were determined using ultrasonic pulse velocity tests. Tensile strength was determined using direct tensile tests (Graybeal et al. [20]). The average properties from 50 replications tested are shown in Table 1.

Forty joints were tested using various geometric combinations as specified in Table 4. The bolt was 9.5 mm (3/8 in.) in diameter and was made of low carbon steel. The *t/d* ratio was small enough to avoid bending deformation of the bolt and induce failure in the UHPFRC element.

Summarization of experimental results and the comparison with the analytical predictions are given in Table 4 and Table 5. The specimens failed mostly in pure tension, as predicted by the analytical model (see Fig. 3).

Figure 3. Net tension failure.

Table 4 Experimental results for UHPC bolted joints

e/d	*b*	A	B	C	D
2	3*d*	7	1.0*p*	12	Tension
6	3*d*	7	1.2*p*	21	Tension
2	10*d*	20	0.7*p*	15	Tension
6	10*d*	6	0.4*p*	32	Tension

where,

A Number of replications
B Experimental longitudinal stress concentration
C Coefficient of variation (%)
D Prevalent failure mode

Table 5 Analytical predictions for UHPC bolted joints

e/d	b	E Equation (5)	F
2	3*d*	1.4*p*	Tension
6	3*d*	1.4*p*	Tension
2	10*d*	1.0*p*	Tension
6	10*d*	1.0*p*	Tension

where,

E Predicted longitudinal stress concentration
F Predicted failure mode

4. CONCLUSIONS

The prediction of stress concentrations in fastened precast concrete plates is a common issue. The focus of this work is to validate an effective analytical method to predict brittle failure modes for different geometries and anisotropic conditions of an UHPC joint. The proposed analytical equations allow estimate the stress concentrations using the elastic properties of the anisotropic material. These predictions correspond reasonably well with those of the analytical solutions found in De Jong [18] and Bickley [19]. Further, laboratory experiments in UHPC joints agree well with the analytical predictions. Most importantly, it is the first time that this analytical model is applied to predict brittle failures of UHPC joints. These results prove that the analytical model originally developed for orthotropic plates can be also applied to UHPC joints. The variability of the experimental dowelled joints results is high. In future projects it would be convenient to increase the number of tests. An efficient and accurate analytical model is certainly an essential precursor to additional experimental studies and numerical models.

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5. CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

6. REFERENCES

[1] Maya LF, Zanuy C, Albajar L, Lopez C, Portabella J. Experimental assessment of connections for precast concrete frames using ultra high performance fiber reinforced concrete. Construction and Building Materials 2013; 48: 173–186. https://doi.org/10.1016/j.conbuildmat.2013.07.002.

[2] Collings TA, Beauchamp MJ. Bearing deflection behaviour of a loaded hole in CFRP. Composites 1984; 15: 33-38. https://doi.org/10.1016/0010-4361(84)90958-3.

[3] Girão Coelho AM, Mottram JT. A review of the behaviour and analysis of bolted connections and joints in pultruded fiber reinforced polymers. Materials & Design 2015; 74: 86–107. https://doi.org/10.1016/j.matdes.2015.02.011.

[4] Hong SG, Chung SH. Experimental study on the behavior of single bolted joints for UHPC panels. IABSE Symposium Report 2015; 105: 1530-1537.

[5] Lee YG, Choi E, Yoon SJ. Effect of geometric parameters on the mechanical behavior of PFRP single bolted connection. Composites Part B: Engineering 2015; 75: 1–10.

[6] Okutan B. The effects of geometric parameters on the failure strength for pin-loaded multi-directional fiber-glass reinforced epoxy laminate. Composites Part B 2002; 33: 567-578. https://doi.org/10.1016/S1359-8368(02)00054-9.

[7] Quinn WJ, Matthews FL. The effect of stacking sequence on the pin-bearing strength in glass fiber reinforced plastic. Journal of Composite Materials 1977; 11: 139-145. https://doi.org/10.1177/002199837701100202.

[8] Wong CM, Matthews FL. A finite element analysis of single and two-hole bolted joints in fiber reinforced plastic. Journal of Composite Materials 1981; 15: 481-491. https://doi.org/10.1177/002199838101500506.

[9] Zhang K, Ueng C. Stresses around a pin-loaded hole in orthotropic plates with arbitrary loading direction. Composite Structures 1985; 3: 119-143. https://doi.org/10.1016/0263-8223(85)90040-6.

[10] Zou X, Wang J. Experimental study on joints and flexural behavior of FRP truss-UHPC hybrid bridge. Composite Structures 2018; 203: 414–424. https://doi.org/10.1016/j.compstruct.2018.06.118.

[11] Koord J, Stüvenc JL, Petersen E, Völkerink O, Hühne C. Investigation of exact analytical solutions for circular notched composite laminates under tensile loading. Composite Structures 2020; 243: 112180. https://doi.org/10.1016/j.compstruct.2020.112180.

[12] Echavarría C, Salenikovich A. Analytical model for predicting brittle failures of bolted timber joints. Materials and Structures 2009; 42: 867–875. https://doi.org/10.1617/s11527-008-9428-0.

[13] Hammoud H, Naaman AE. Ferrocement bolted shear joints: failure modes and strength prediction. Cement and Concrete Composites 1998; 20: 13-29. https://doi.org/10.1016/S0958-9465(97)87389-1.

[14] Mansur MA, Tan KL, Naaman AE. Strength of bolted moment connections in ferrocement construction. Cement and Concrete Composites 2010; 32: 532–543. https://doi.org/10.1016/j.cemconcomp.2010.04.001.

DOI: https://doi.org/10.21501/21454086.3715

[15] Kwon Y, Chung S, Hong S. Strength and behavior of bolted ultra-high performance concrete panel joint with geometric parameter. Journal of Applied Mechanical Engineering 2017; 6: 261. https://doi.org/10.4172/2168-9873.1000261.

[16] Camacho E, Serna P, López JA. UHPFRC bolted joints: failure modes of a new simple connection system. High Performance Fiber Reinforced Cement Composites RILEM 2012; 6: 421-428.

[17] Echavarría C. Analyse d'une plaque orthotrope avec trou: Application aux assemblages en bois. Ph.D. thesis N° 2947, Swiss Federal Institute of Technology Lausanne EPFL, Switzerland 2004.

[18] De Jong T. Stresses around pin-loaded holes in elastically orthotropic or isotropic plates. Journal of Composite Materials 1977; 11: 313-331. https://doi.org/10.1177/002199837701100306.

[19] Bickley W. The distribution of stress round a circular hole in a plate. Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character 1928; 227: 383-415. https://doi.org/10.1098/rsta.1928.0010.

[20] Graybeal B, Florent B. Development of direct tension test method for ultra-high-performance fiber-reinforced concrete. ACI Materials Journal 2013; 110: 177-186.