Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (45) No. (1) January 2023

Effect of load eccentricity on the capacity of branch plate-to-CHS connection subjected to shear loading.

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الملخص العربى :

هذا البحث يقدم دراسة معملية لوصلات الألواح الفرعية المتصلة بعمود من القطاعات المفرغة المستديرة والتي تتعرض لتحميل قوي قص ذات إزاحة من وجة القطاع. يلاحظ أن مثل هذه الوصلات تواجه بشكل عام انخفاضا كبيرا في القدرة بسبب الحد الأدنى المسموح به لتشوه القطاع المفرغ المستدير. لزيادة قدرة هذه الوصلات تستخدم تقنيات تقوية مختلفة مثل ملء القطاع المفرغ بالخرسانة أو التدعيم بإستخدام الأعصاب الحلقية أو بإستخدام الألواح الفرعية المخترقة للقطاع. تم إجراء دراسة معملية تتألف من أربعة عينات لتحديد سلوك الألواح الفرعية المتصلة بالقطاعات المفرغة المستديرة. وبدراسة حالات الإنهيار لهذه الوصلات وجد أنه يحدث تشوه دائم لسطح القطاع المفرغ عند نقطة الإتصال بالألوح الفرعية متبوعة بحدوث قص ثاقب جهة الشد من الألواح الفرعية. تكشف الدراسة أن الإزاحة الخاصة بحمل القص لها تأثير كبير علي سعة العزوم لهذا النوع من الوصلات وذلك بسبب تأثر ال القص المتأخر علي سطح الإتصال وأخيرا تم عمل مقارنة مع دليل التصميم الحالي للنوع المشابه من الوصلات.

Abstract.

This paper presents an experimental investigation of beam-to-CHS column branch plate connections subjected to eccentric shear loading. It is observed that such connections generally experience a significant decrease in capacity due to the low deformation limit of the hollow section. To increase the capacity of such connections, various stiffening techniques such as grout filling, ring stiffener, collar plate and/or through plate are usually employed. An experimental investigation consisting of four specimens was conducted to determine the behaviour of the branch plate-to-CHS connection. The failure modes of all specimens were excessive chord surface deformations followed by chord face punching at the tension side of the branch plate. The study reveals that load eccentricity has a significant effect on the moment capacity of this type of connection due to the effect of shear lag on the chord face. Finally, a comparison with the current design guidelines was conducted.

Keywords: CHS, Branch plate, Shear, Connections, Eccentricity.

INTRODUCTION

In recent decades, the joints of hollow sections have attracted considerable research interest, owing to their unique structural characteristics and complex mechanics. As such, various advanced analytical techniques and sophisticated numerical models have been developed to explore the behavior of these joints under different loading conditions. Such research has led to numerous innovations and advancements in the design and construction of hollow section joints, with the ultimate goal of ensuring their safe and efficient application in real-world structures.

In the last three decades, Hollow Structural Sections (HSS) have become increasingly popular among both architectural and structural engineers due to their aesthetically pleasing appearance and high strength-to-weight ratio (Voth & Packer, 2012a). HSS offers engineers the ability to span large distances with relatively low weight, while also providing an attractive exposed steel member. The joints of these hollow sections have been the focus of much research in recent years. However, the load carrying capacity limited by the 3% d0 deformation limit of the chord member diameter and for the SHS and RHS the face width (Lu, de Winkel, Yu, & Wardenier, 1994). Voth and Packer (Voth & Packer, 2012a), (Voth & Packer, 2012b) and (Voth & Packer, 2012c) studied the behaviour of the branch plate-to-CHS subjected to axial loading in both compression and tension loading, they reveals that the orientation of the branch plate, the branch plate depth -to-CHS ratio (h = h/D_0), the chord member slenderness, and weld size; generally The configuration of a connection can have a significant impact on its capacity. In addition, the through plate configuration is a common strengthening technique used to increase the capacity of a connection. By subjecting branch plates to both compression and tension, the through plate configuration can effectively double the capacity of the connection. (Shaat & Fam, 2009), (Abdallah, Shaat, & Sayed-Ahmed, 2016) and (Sayed-Ahmed, Shaat, & Abdallah, 2018) strengthen the slender SHS columns using CFRP and the sections have a good enhancement in both strength and stiffness. (Zapata, El Aghoury, Shaat, & Graciano, 2019) studied the behaviour of the longitudinal branch plate-to-CHS subjected to compression loading and predicted an analytical model considering the plastic behaviour for this type of connection. The authors (Abdallah, El Aghoury, Ibrahim, & Shaat, 2023) did an extensive numerical investigation on the behavior of T-type branch plate-to-CHS connections under eccentric shear loading and revealed that the load eccentricity has a significant effect on the connection capacity, due to shear lag effect of the eccentric shear load. They proposed a modification factor for the current design guidelines CIDECT 2008 (Kurobane, Packer, Wardenier, & Yeomans, 2004) AISC 360-10 (360-10, 2010).

This study aims to further investigate the behavior of branch plates under eccentric shear loading in CHS connections. Specifically, a focus will be paid to the impact of shear loading eccentricity on the connection's capacity and behavior. We will present and discuss the results of experimental testing conducted on four specimens subjected to eccentric shear loading. Additionally, we will verify our experimental findings using finite element modeling (FEM).

Furthermore, an extensive parametric study will be conducted to explore the effect of load eccentricity on the connection's behavior and capacity. Through this study, we hope to gain a deeper understanding of how the behavior of CHS connections under eccentric shear loading is affected by various factors. The main goal is to provide valuable insights that can inform the design and construction of these types of connections in the future.

Experimental Program

Four specimens, in the form of circular hollow section columns (CHS 114*4.0) welded to a branch plate with a thickness of 20.0 mm using a 10 mm weld size, were subjected to eccentric shear loading, as illustrated in Figure 1. The study focused on two main parameters: load eccentricity from the chord face (e_1), with values of $0.50D_0$ and $1.50D_0$, and branch plate depth to the chord member diameter (η_1), with values of $0.50D_0$ and $1.50D_0$, as presented in Table 3.

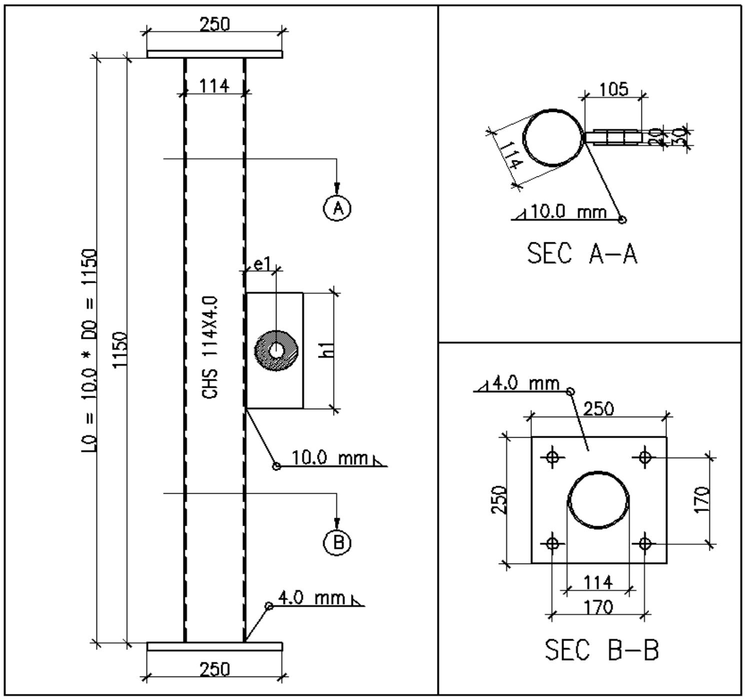

Figure 1 Geometrical parameters of specimens

Geometrical and Material properties

The connections were designed with a consistent width-to-depth ratio (β) and a radius-to-thickness ratio (γ) of the column chord set at 28.50, while the depth-to-thickness ratio (η) is varied through the specimens. The chords were made from ASTM A500/A500M-10 (ASTM 2010) Grade C cold-formed circular hollow sections (CHS) with a nominal diameter (d0) of 114 mm and a thickness (t_0) of 4.0 mm. The steel has a specified yield strength of 600 MPa and an ultimate strength of 700 MPa. Both the branch and end plates were fabricated from CAN/CSA-G40.20-04/G40.21-04 (CSA 2004) Grade 300 W wrought steel, which has a nominal thickness of 20 mm for the branch plate and 10 mm for the end plates and a minimum specified yield strength of 235 MPa.

All connections were fabricated using noncritical fillet welds with a nominal leg size (w) of 10 mm and a matching E49XX electrode (CSA 2003). They were designed to carry full plate capacity. The average geometrical properties for the experimental specimens are listed the Table 3 which agreed with Figure 1.

Table 3 Average measured geometrical properties

Connection ID	D_0	T_0	L_0	Ecc.	h_1	η	Fy	Fu
	(mm)	(mm)	(mm)	(mm)	(mm)		(MPa)	(MPa)
CB-114-4-1.0D-0.50D	115.1	3.22	1152	57	114	1.0	634	665
CB-114-4-2.0D-0.50D	115.2	3.20	1154	57	228	2.0	653	677
CB-114-4-1.0D-1.50D	114.6	3.12	1150	171	114	1.0	365*	406*
CB-114-4-2.0D-1.50D	113.8	3.20	1149	171	228	2.0	634	692

The coupon test results of this specimen indicates that it is made of mild steel.

Method of testing and instrumentation

All specimens were tested using a quasi-static testing machine connected to a data acquisition system, which collected data on the load, displacements, and strains. All connections were tested in the configuration illustrated in Figure 1. where plate displacement was applied by the upper assembly with reaction force taken by the stiff reaction. The moment frame, along with the reaction yoke and lower assembly, provided the reaction forces to balance the loads and brace the assembly.

The testing was conducted slowly and controlled to remain within the quasi-static regime. The T-type connections were connected to the lower beam using a four bolts moment connection while the upper connection acts as a lateral support only, all specimens were kept vertical and tested through the closed frame. As shown in Figure 2, all connections were instrumented using two Linear Variable differential Transformers (LVDTs) to measure the vertical displacement of the branch plate (d_1) and the ovalization of the chord section (d_2), as well as, the strain under and upper the branch plate were measured also (S_1 and S_2).

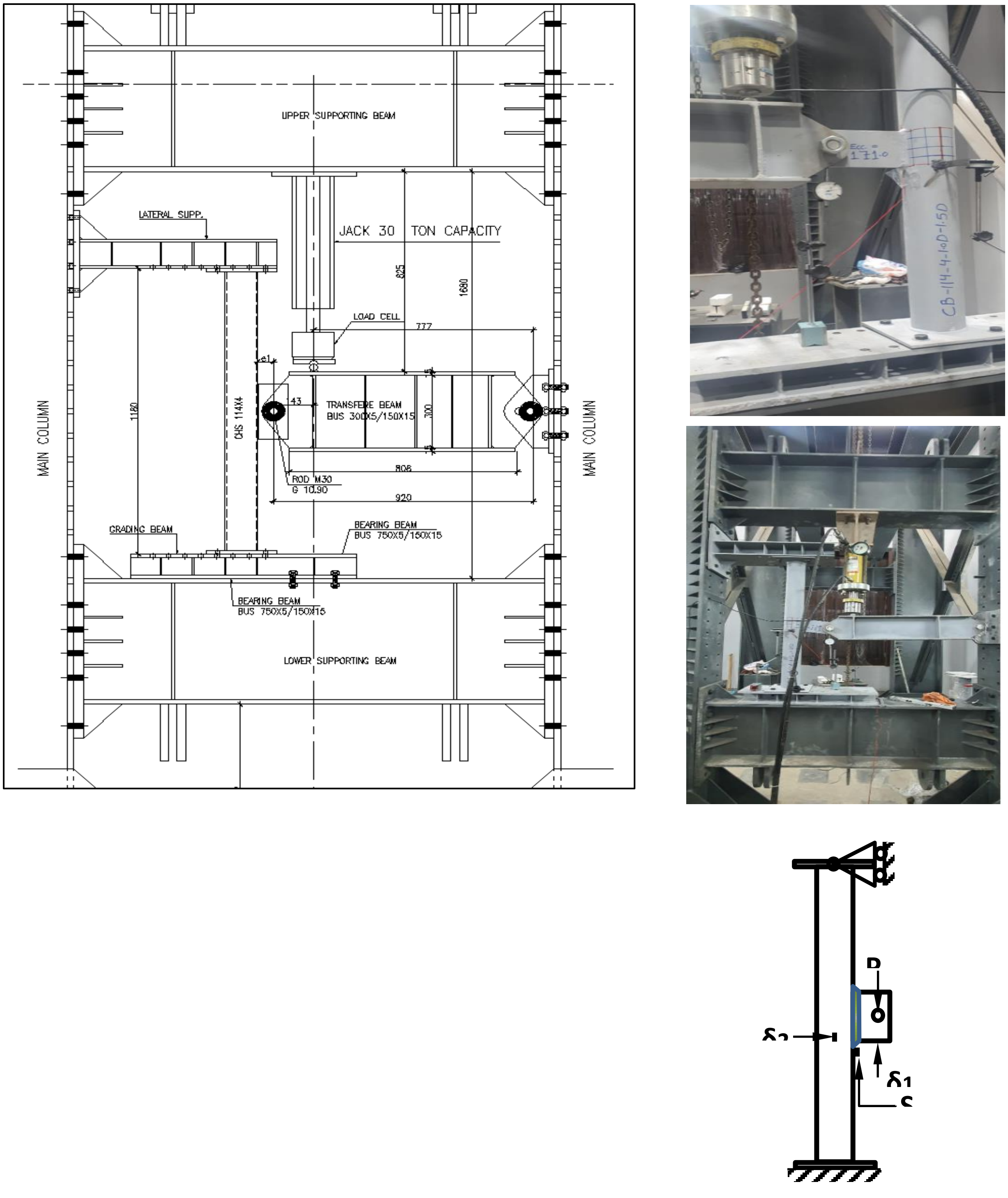

Figure 2 Experimental setup for the tested connections

Experimental Results and Observations

During the testing of all specimens, eccentric shear loading was applied, resulting in in-plane bending on the branch plate in addition to the shear force. As a consequence of this bending moment, excessive deformations were observed on the chord face, with the upper side experiencing tension force and the lower side experiencing compression force. Ultimately, all connections failed due to punching shear (PS) around the weld toe, serving as their ultimate failure mechanism. The load-deformation curve can provide an effective summary of the connection behavior and capacity. The connection load capacity (N_u) can be determined by considering the minimum value from two limit states. The first limit state is the load capacity at the 3% d_0 deformation limit for specimens that exhibit a large deformation at chord faces ($N_{3\%}$). The second limit state is the punching shear failure at the tension side from the chord face (N_{ps}). Figure 3 shows a comparison of the load-deformation responses for specimens having the same load eccentricity = 0.50 D_0 with h = 1.0 D_0 and h = 2.0 D_0 while in Figure 4 the load eccentricity = 1.50 D_0. Similarly, Figure 5 shows a comparison of the load-deformation responses for specimens with h = 1.0 D_0, eccentricity = 0.50 D_0 and 1.50 D_0 while in Figure 6 the specimens with h = 2.0 D_0, eccentricity = 0.50 D_0 and 1.50 D_0. The load capacity at the 3% deformation limit cannot be determined in these specimens because the deformation measurement beneath the branch plate was not taken perpendicular to the chord face. To accurately determine the load capacity at the 3% D0 deformation limit, it is necessary to first validate the results using an appropriate Finite Element Model (FEM). Once the results are validated, the measured data can be extrapolated to determine the load capacity

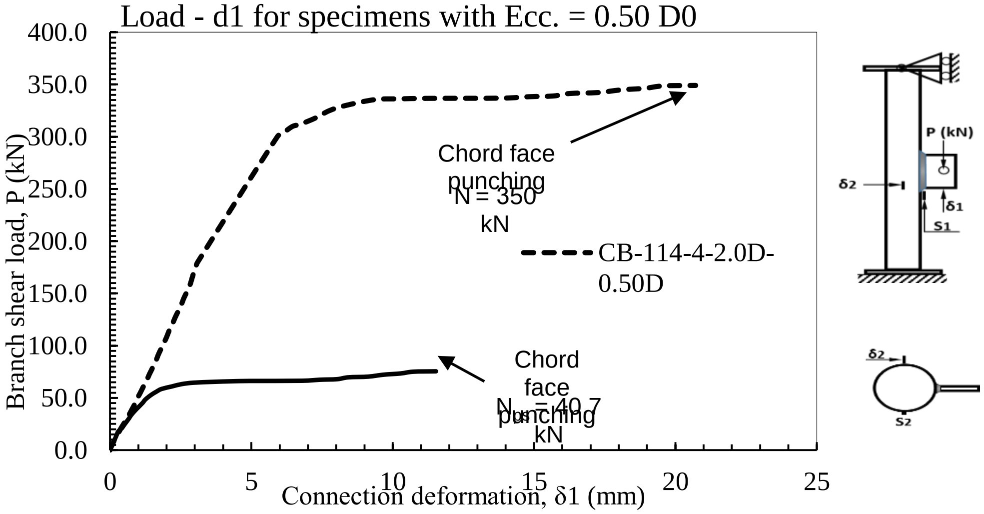

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Figure 3 Load deformation behaviour of plate-to-CHS for specimens with Ecc. = 0.50 D_0

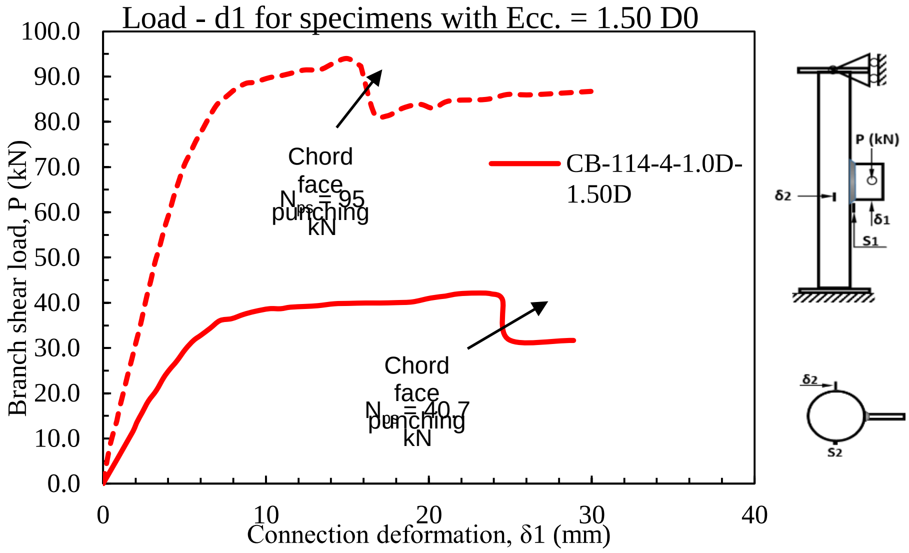

Figure 4 Load deformation behaviour of plate-to-CHS for specimens with Ecc. = 1.50 D_0

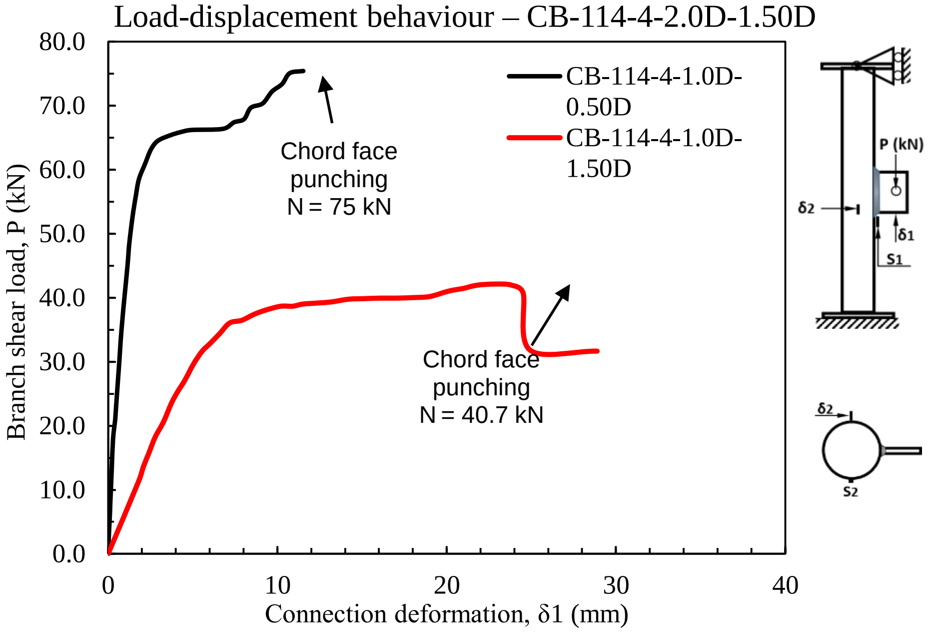

Figure 5 Load deformation behaviour of plate-to-CHS for specimens with h = 1.0 D_0

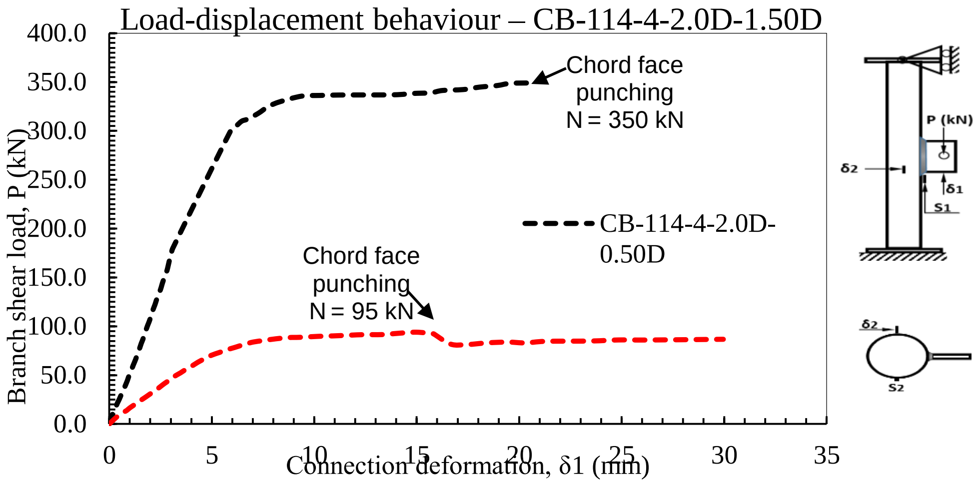

Figure 6 Load deformation behaviour of plate-to-CHS for specimens with h = 2.0 D_0

According to the recommendations by (Van der Vegte & Makino, 2006) and (van der Vegte & Makino, 2007), the length of the tested specimen (L0) should be at least ten times the chord diameter to exclude the effect of the end condition on the connection behaviour and capacity. This criterion is met in the tested specimens. So, it is important to compare the load capacity of the tested specimens to the current Design guidelines. However, measuring the perpendicular deformation of the chord face can be challenging due to the small diameter of the specimen. Therefore, it may be difficult to obtain accurate measurements for comparison.

Effect of load eccentricity on the connection moment capacity

From the current Design guide lines, CIDECT 2008 (Wardenier, Kurobane, Packer, Van der Vegte, & Zhao, 2008) and AISC (360-10, 2010), the moment capacity for this type of connection can be calculated using the following equations as: -

$$M_{CIDECT} = 0.9 * 4\, Fy_0\, t_0^2\, h_1 (1+0.40\, \eta)\, Q_f \qquad \text{(Eqn. 1)}$$

$$M_{AISC} = 4.40\, Fy_0\, t_0^2\, h_1 (1+0.25\, \eta)\, Q_f \qquad \text{(Eqn. 2)}$$

$$1.0 < \eta < 4.0$$

In this study, the factor Q_f is taken as 1 since there are no external stresses applied to the tested chord, except for the eccentric shear loading. Therefore, the chord stress level is solely affected by the eccentric shear loading. When applying the equations, two capacities are obtained for the four specimens since the eccentricity is not taken into account. It was expected that the CB-114-4.0-1.0D-0.50D specimen would provide a load capacity three times that of the CB-114-4.0-

1.0D-1.50D specimen, and the same for the CB-114-4.0-2.0D-0.50D and CB-114-4.0-2.0D-1.50D specimens. However, after testing and plotting the results Figure 5 and Figure 6, the load capacities did not match the expected results. For specimens with small eccentricity, the load capacity was 1.875 times that of the large eccentricity, while for specimens with large h value, the load capacity was 3.68 times that of the large eccentricity. This conclusion is consistent with previous research (Abdallah et al., 2023) that found the eccentricity has a significant effect on the moment capacity of these types of connections, which is attributed to the effect of shear lag.

Effect of load eccentricity on the connection moment capacity

The depth of the branch plate relative to the chord diameter ratio (h) has a significant effect on the moment capacity of the connections, as demonstrated in Figure 3 and Figure 4. These results are consistent with the findings of Equations 1 and 2. As the value of h increases, the moment capacity also increases, since the larger depth from the chord face is more affected by moment and the chord face is relatively affected by smaller stress values compared to specimens with a smaller h.

Conclusion

An experimental investigation was conducted on branch plate-CHS connections subjected to shear loading. Four specimens were tested under eccentric shear loading, and the studied parameters were the load eccentricity and the ratio of branch plate depth to CHS diameter. Based on the results, the following conclusions can be drawn:

- The failure modes of all specimens were excessive chord surface deformations followed by chord face punching at the tension side of the branch plate.
- The branch plate (h) values have a significant effect on the connection moment capacity. As the h increases the moment capacity increases also, which agreed with the current design guidelines.
- The moment capacity of this connection is significantly affected by the load eccentricity. As the load eccentricity value increases, the moment capacity of the connection decreases, which is not considered in the available design guidelines.
- A comprehensive FEM investigation is necessary to understand the impact of shear lag on the chord face at the connection to the branch plate for this type of connection.
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