Design of concrete-filled high strength steel tubular X-joints subjected to compression

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Abstract

Design of concrete-filled high strength steel tubular X-joints subjected to compression is examined. A numerical investigation on concrete-filled high strength steel square and rectangular hollow section X-joints is presented in this paper. The high strength steel tubes had nominal yield stresses of 700 and 900 MPa. The infilled concrete had nominal concrete cylinder strengths of 35 and 100 MPa. A finite element model was developed and validated against test results. On validation of the finite element model, a parametric study comprised 156 finite element analyses was undertaken using the validated model. The strengths of the concrete-filled high strength steel tubular X-joints obtained from the parametric study together with available test results in the literature were compared with the nominal strengths calculated from the CIDECT Design Guide. It is shown that the CIDECT design predictions exhibited significant scatter and generally conservative for the concrete-filled high strength steel tubular X-joints. However, the CIDECT predictions overestimated the strengths of the concrete-filled high strength steel tubular X-joints with chord sidewall slenderness ratio exceeded 50. Hence, new design rules are proposed for concrete-filled high strength steel square and rectangular hollow section X-joints subjected to compression. It is shown that the proposed design rules are able to provide reasonably good predictions.

Keywords: Cold-formed steel; Concrete-filled; Connections; Finite-element analysis; High strength steel; Tubular joints.

1. Introduction

Design provisions for concrete-filled tubular joints are available in the Comité International pour Ie Développement et l'Étude de la Construction Tubulaire (CIDECT) Design Guide [1], which is the only existing guideline that provides specific provisions for designing concrete-filled tubular joints. It is noteworthy that for concrete-filled square and rectangular hollow section X-joints under compression, the CIDECT [1] design provisions were developed based on 11 concrete-filled X-joint tests. These 11 tests, as reported in Packer [2], had the measured yield stress on steel tubes of 330 MPa. High strength steels are becoming increasingly attractive in a range of structural applications. Although several experimental investigations [3-6] were carried out on concrete-filled tubular chords under concentrated bearing loads, research into concrete-filled high strength steel tubular joints has been rather limited.

An experimental investigation on concrete-filled high strength steel square and rectangular hollow section X-joints subjected to compression was initiated by the authors [7]. The data obtained from the test program [7] are limited and the test specimens covered nominal chord sidewall slenderness ratio up to 40. In this study, a finite element (FE) model was first developed to replicate the concrete-filled tubular X-joint tests as reported in [7]. After validation of the FE model, a parametric study comprised of 156 FE analyses was performed to generate further numerical data over a wider range of key joint parameters (e.g., chord sidewall slenderness ratio, chord aspect ratio, chord width to thickness ratio and brace to chord width ratio). The investigated chord sidewall slenderness ratio in the parametric study was up to 90. The appropriateness of the design provisions in the CIDECT [1] to concrete-filled high strength steel tubular X-joint was assessed based on the

numerical and experimental results. New design rules are proposed for concrete-filled high strength steel tubular X-joints subjected to compression.

2. Summary of test program

A series of concrete-filled high strength steel square and rectangular hollow section X-joints subjected to compression have been tested by the authors [7]. In order to avoid brace failure and to reveal the true capacity of the compression-loaded concrete-filled tubular X-joints, steel bearing plates were used to simulate the braces. This method has also been used by Packer [2], based on which the CIDECT design provisions for concrete-filled tubular X-joints under compression were developed.

The concrete-filled high strength steel tubular X-joints had measured chord aspect ratio (h_0/b_0) varied between 0.5 and 1.7, brace to chord width ratio (b_1/b_0) varied between 0.33 and 0.83, chord sidewall slenderness ratio (h_0/t_0) ranged from 12.6 to 40.6, and chord width to thickness ratio (b_0/t_0) ranged from 20.3 to 30.9. The definition of symbols for the X-joints are shown in Figure 1. The investigated high strength steel sections had two nominal steel grades: 700 and 900 MPa. The steel grades can be identified from the cross-section labels of the steel tubes, where "H" and "V" represent nominal steel grades of 700 and 900 MPa, respectively. The measured 0.2% proof stresses from tensile flat coupon tests ranged from 679 to 997 MPa. The high strength steel tubular chords were infilled with normal strength concrete (NSC) and high strength concrete (HSC). The NSC (grade C35) and HSC (grade C100) had measured concrete cylinder strengths of 36.4 and 95.7 MPa, respectively. The experimental investigation is detailed in Li and Young [7].

3. Numerical modelling approach

3.1. Finite element model

A finite element (FE) model was developed using FE package ABAQUS [8] to simulate the concrete-filled high strength steel tubular X-joint tests reported by Li and Young [7]. The FE model was built based on measured geometries. The measured stress-strain curves obtained from tensile coupon tests were used for the cold-formed high strength steel tubes. The experimentally obtained stress-strain curves were converted to true stress and true plastic strain curves before incorporating into the model. For the material properties of the concrete infills, the concrete damaged plasticity model that provided by the ABAQUS [8] was used. The employed dilation angle and flow potential eccentricity were 40° and 0.1, respectively. The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress, and the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian were taken as 1.16 and 0.6, respectively. To model the compressive behaviour of the confined concrete infills, the uniaxial constitutive confined concrete model used by Yang et al. [9] was adopted in this study.

A 4-node quadrilateral shell element S4R was selected to simulate the high strength steel tube, while an 8-node solid element C3D8R was employed to simulate the infilled concrete. The braces of the X-joint, which were simulated by solid steel bearing plates, were modelled using discrete rigid 3D elements. The mesh sizes were studied to achieve suitably accurate results within reasonable computational time. The employed mesh sizes ranged from approximately 6 to 12 mm depending on the size of the tubular sections and finer meshes were used at the corner regions. The structured mesh technique was used in order to achieve proper hexahedral elements.

The interfaces between the high strength steel tubes and their concrete infills were modelled through contact pairs. The surface-to-surface discretization contact approach was applied. The master surfaces were defined in the concrete infill, whereas the slave surfaces were defined in the steel tube. The friction penalty contact with a friction coefficient of 0.6 in the tangential direction was used. The pressure-overclosure relationship in the normal direction used the "hard" contact and allowed separation. The braces of the concrete-filled tubular X-joint were modelled through solid rigid plates. Surface-to-surface contact was also used to define the interfaces between the chords and the solid rigid plates, and the friction penalty contact with a friction coefficient of 0.4 was applied.
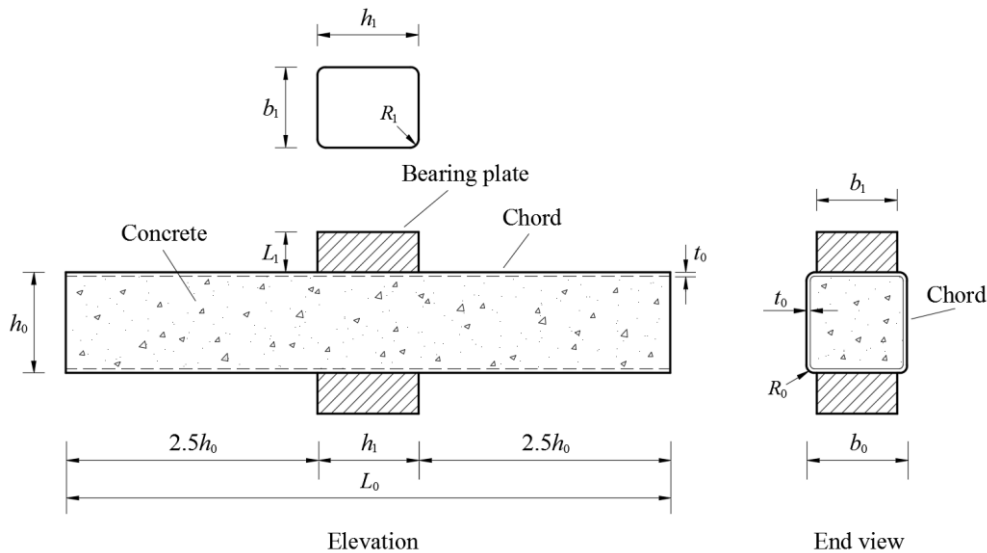
Fig. 1. Definition of symbols for concrete-filled high strength steel tubular X-joints.

The boundary conditions of the tubular X-joint were modelled in accordance with the test. It is noteworthy that the geometries, boundary conditions and failure modes of the test specimens were symmetric. Hence, only one-quarter of the test specimens were modelled and suitable symmetry boundary conditions were applied accordingly. The compressive loads were applied by specifying axial displacements to the reference points of the bearing plates, which was identical to the tests using displacement control.

3.2. Validation of finite element model

The FE model was validated against the test results in terms of ultimate strengths, failure modes and load-deformation curves. The ultimate strengths obtained experimentally (N_{Exp}) and numerically (N_{FEA}) are compared in Table 1. The mean value of the N_{Exp}/N_{FEA} is 0.99 with the corresponding coefficient of variation (COV) of 0.093. Typical numerical failure modes derived from the FE analyses are compared with the corresponding experimental failure modes in Figures 2 and 3. Typical load-deformation curves obtained from the FE analyses are also compared with the corresponding experimental curves in Figure 4. Overall, it is shown that the developed FE model is capable of replicating the experimental ultimate strengths, failure modes and load-deformation histories.

Table 1. Comparison of ultimate strengths obtained from FE analyses with test strengths.

| Specimen	b_1/b_0	b_0/t_0	h_0/t_0	N_{Exp} (kN)	N_{FEA} (kN)	N_{Exp}/N_{FEA}
X-H100×100×4-40×40-C35	0.39	25.6	25.5	289.5	281.3	1.03
X-H100×100×4-40×80-C35	0.80	25.5	25.5	398.4	440.9	0.90
X-H100×100×4-100×80-C35	0.80	25.6	25.6	746.5	740.5	1.01
X-H120×120×4-40×40-C35	0.33	30.8	30.8	305.2	294.5	1.04
X-H120×120×4-40×40-C100	0.33	30.8	30.7	431.3	417.0	1.03
X-H120×120×4-80×100-C35	0.83	30.9	30.8	686.8	726.6	0.95
X-H120×120×4-80×100-C100	0.83	30.9	30.8	1174.1	1185.8	0.99
X-H50×100×4-40×80-C35	0.80	25.3	12.6	910.0	1017.5	0.89
X-H50×100×4-40×80-C35-R	0.80	25.3	12.6	892.2	1016.4	0.88
X-H50×100×4-40×80-C100	0.80	25.4	12.7	981.2	1094.6	0.90
X-H50×100×4-100×80-C100	0.80	25.4	12.7	4138.2	3372.7	1.23
X-H200×120×5-120×80-C35	0.67	24.2	40.6	721.9	651.4	1.11
X-V80×80×4-40×40-C35	0.49	20.4	20.3	338.5	355.4	0.95
X-V80×80×4-40×40-C100	0.49	20.3	20.3	464.0	453.5	1.02
X-V80×80×4-80×40-C35	0.50	20.3	20.3	569.2	588.7	0.97
					Mean	0.99
					COV	0.093

(a) Experimental failure mode
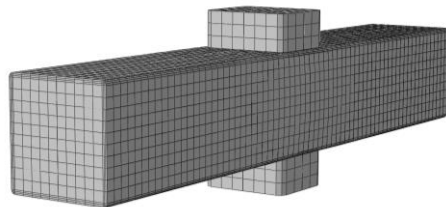
(b) Numerical failure mode
Fig. 2. Experimental and numerical failure modes of specimen X-H120×120×4-80×100-C100.
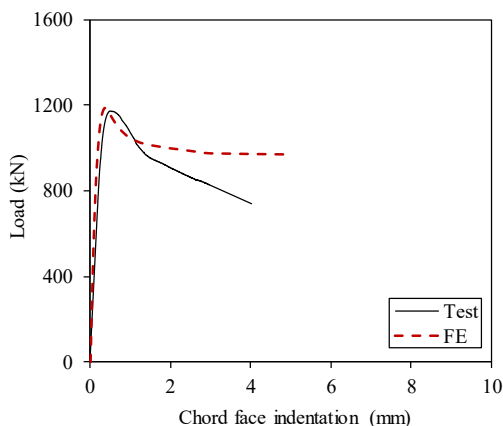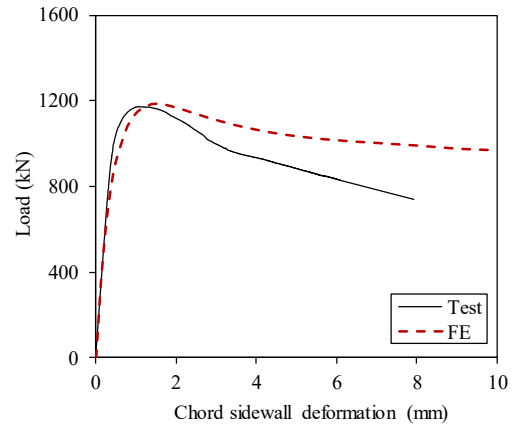

(a) Experimental failure mode
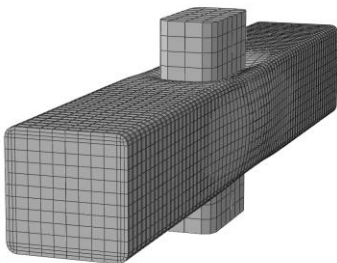
(b) Numerical failure mode
Fig. 3. Experimental and numerical failure modes of specimen X-V80×80×4-80×40-C35.

(a) Load-chord face indentation curves

(b) Load-chord sidewall deformation curves
Fig. 4. Comparison of test and FE load-deformation curves of specimen X-H120×120×4-80×100-C100.

3.3. Parametric study

The test program reported by the authors [7] covered concrete-filled high strength steel tubular X-joints with the b_1/b_0 ratio from 0.33 to 0.83, b_0/t_0 ratio from 20.3 to 30.9, h_0/t_0 ratio from 12.6 to 40.6, and h_0/b_0 ratio from 0.5 to 1.7. In order to expand the database, a parametric study was undertaken using the validated model to generate further numerical data over a wider range of the key joint parameters.

In the parametric study, the chord members covered 26 different square and rectangular hollow sections. These tubular sections were selected from the range of practical cross-section sizes for structural applications. The selected sections had overall depths ranged from 140 to 400 mm, overall widths ranged from 100 to 400 mm, and steel wall thicknesses ranged from 2 to 10 mm. The steel grades of the square and rectangular hollow sections were 700 and 900 MPa, being referred as "H" and "V" series, respectively. The measured material properties obtained from the coupon tests of sections H100×100×4 and V80×80×4 were used for the "H" and "V" series, respectively. The lengths of the chords were designed such that the clear distance from the end of the chord member to the edge of the steel bearing plate was $2.5h_0$, as illustrated in Figure 1. For each concrete-filled high strength steel tubular chord member, 3 different sizes of bearing plates were designed to simulate different brace members. Both NSC (C35) and HSC (C100) infills were studied and the tubular chord members were infilled with grade C35 or C100 concrete along their full chord lengths.

In total, 156 parametric results were generated. The concrete-filled high strength steel tubular X-joints in the parametric study had b_1/b_0 ratio ranged from 0.25 to 0.93, b_0/t_0 ratio ranged from 15 to 90, h_0/t_0 ratio ranged from 15 to 90 and h_0/b_0 ratio ranged from 0.5 to 2.5. It should be noted that the investigated h_0/b_0 ratio goes beyond the CIDECT [1] limit of 1.4. The ultimate strengths (N_{FEA}) of the specimens in the parametric study were obtained. Note that the ultimate strengths were taken as the peak load or the load of 3%b_0 deformation limit as specified in the CIDECT, whichever occurs earlier in the load-chord face indentation curves. The same approach has been employed by the authors [7] to determine the ultimate strengths of concrete-filled high strength steel tubular X-joints in the test program.

4. CIDECT design provisions and comparison with joint strengths

Design provisions for concrete-filled square and rectangular hollow section X-joints are available in the current CIDECT Design Guide No.3 [1]. The CIDECT [1] is also the only existing design guideline that has specific provisions for concrete-filled tubular joints. For concrete-filled tubular X-joints with braces in compression, the CIDECT design provisions were developed based on the research carried out by Packer [2], where a total of 11 concrete-filled X-joint specimens were tested. The design provisions were derived from concrete bearing models and the contribution of the steel tube was ignored to form a conservative lower bound method. The equation recommended by the CIDECT for compression-loaded concrete-filled square and rectangular hollow section X-joints with braces perpendicular to the chords can be illustrated as follows,

$$N_{CIDECT} = A_1 f'_c (A_2/A_1)^{0.5} \qquad (1)$$

where, N_{CIDECT} is the nominal strength; f'_c is the compressive cylinder strength of the infilled concrete; $A_1 = b_1 h_1$ is the bearing area over which the transverse bearing load applied; A_2 is the dispersed bearing area. It is specified in the CIDECT [1] that the A_2 shall be determined by dispersion of the bearing load at a slope of 2:1 longitudinally along the chord and the dispersed bearing area A_2 equals to $b_1(h_1+2h_0)$. It is noteworthy that the CIDECT [1] restricts the

$(A_2/A_1)^{0.5}$ values with an upper limit of 3.3 for concrete-filled X-joints.

The feasibility of applying the CIDECT design provisions to concrete-filled high strength steel tubular X-joints is evaluated herein by comparing the test and FE strengths (N_u) with the nominal strengths (N_{CIDECT}) predicted by the CIDECT [1]. A total of 171 available data was used for the comparison, including 15 test data [7] and 156 numerical data obtained in this study. The comparison results are tabulated in Table 2 where the mean value of the N_u/N_{CIDECT} ratio is 1.24 with a very large COV of 0.852. The comparison results are also graphically shown in Figure 5, where the N_u/N_{CIDECT} values exhibit significant scatter and the N_u/N_{CIDECT} ratio generally decreases as the h_0/t_0 ratio increases. For relatively stocky steel sections ($h_0/t_0 \leq 20$), the CIDECT predictions are always overly conservative. One of the possible reasons for this could be due to the contribution of the steel tube is ignored in the CIDECT design formula. In addition, the N_u/N_{CIDECT} values for the specimens with NSC (normal strength concrete) are always greater than their HSC (high strength concrete) counterparts. This may be explained by the fact that the CIDECT design provisions consider the same degree of confinement for different concrete infills.

Table 2. Comparison of test and FE results with design predictions.

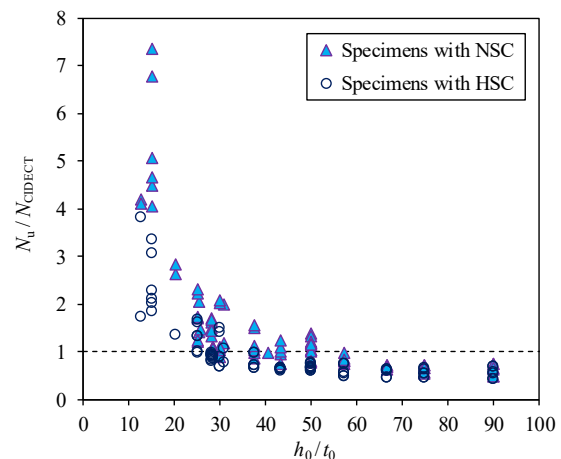| Parameters	N_u/N_{CIDECT}	N_u/N_p
No. of specimens	171	171
Mean	1.24	1.06
COV	0.852	0.235

Fig. 5. Comparison of test and FE results with CIDECT predictions.

Overall, the design provisions in the CIDECT [1] provide conservative strength predictions for the high strength steel tubular X-joints filled with NSC for h_0/t_0 ratio up to 40, as shown in Figure 5. For the X-joints filled with HSC, the CIDECT [1] design provisions give generally conservative predictions for h_0/t_0 ratio up to 25, beyond which the CIDECT design provisions generally yield over-optimistic predictions. It should be noted that the design provisions recommended by the CIDECT [1] were developed on the basis of concrete-filled X-joint tests with chord sidewall slenderness ratio varied between 26.9 and 37.4. Besides, the infilled concrete of these tests had cylinder strengths of 43.3 MPa and the yield stress of the steel tubes was 330 MPa. The CIDECT [1] design provisions consider the concrete confinement effect through the $(A_2/A_1)^{0.5}$ value only, which is irrelevant to the materials, steel wall thickness and chord sidewall slenderness ratio. It is found that the A_2 determined by dispersing the bearing area longitudinally at a slope of 2:1 to the centre depth of the chord could lead to unconservative predictions for concrete-filled tubular X-joints with relatively slender steel sections. In this study, the CIDECT [1] design provisions overestimate the strengths of the concrete-filled high strength steel tubular X-joints with chord sidewall slenderness ratio above 50.

5. Proposed design rules and comparison with joint strengths

In this study, new design rules are proposed for concrete-filled high strength steel tubular X-joints subjected to compression. The proposed design rules consider the contribution of the high strength steel tube as well as the confinement effect of the concrete. The proposed formula is expressed in Eq. (2), where N_P is the proposed nominal strength, N_s is the joint strength contributed by the high strength steel tubular section, N_c is the joint strength contributed by the concrete; A_s and f_{y0} are the cross-sectional area and yield stress of the high strength steel section, respectively; A_c and f_c' are the cross-sectional area and the cylinder strength of the concrete infill, respectively.

$$N_P = N_s + N_c \left[0.9 + 1.3 \frac{t_0}{h_0} \left(\frac{A_s f_{y0}}{A_c f_c'} \right)^2 \right] \qquad (2)$$

In Eq. (2), the calculation of the N_s employed the design formulae in Table 7.11 of the European Code [10]. For X-joints with braces perpendicular to the chords, the N_s is to be obtained as follows,

For $\beta = 1.0$ ($b_1/b_0 = 1.0$):

$$N_s = k_n f_b t_0 \left(2h_1 + 10t_0 \right) \qquad (3)$$

For $\beta \leq 0.85$ ($b_1/b_0 \leq 0.85$):

$$N_s = \frac{k_n f_{y0} t_0^2}{(1-\beta)} \left(\frac{2h_1}{b_0} + 4\sqrt{1-\beta} \right) \qquad (4)$$

For $0.85 < \beta < 1.0$ ($0.85 < b_1/b_0 < 1.0$), the N_s can be obtained by using linear interpolation between the value at $\beta = 0.85$ and the governing value at $\beta = 1.0$. In Eqs. (3) and (4), k_n is the chord stress function and the f_b is the chord sidewall flexural buckling stress as detailed in Table 7.11 of the European Code [10]. In this study, the value of k_n was taken as 1.0.

The calculation of the N_c is shown in Eq. (5), which was developed in the same way as the current CIDECT [1] design provisions.

$$N_c = A_1 f_c' \left(A_2/A_1 \right)^{0.5} \qquad (5)$$

where, f_c' is the compressive concrete cylinder strength; $A_1 = b_1 h_1$ is the bearing area over which the transverse load is applied; A_2 is the dispersed bearing area. It should be noted that instead of dispersing the bearing load longitudinally only, the A_2 was determined by dispersion of the bearing load in both the longitudinal and lateral directions along the chord member in the concrete area. The dispersion slope of 1:1 in both the longitudinal and lateral directions that recommended by Feng and Young [11] was adopted in calculating the A_2.

The comparison results of the N_u with the N_p are shown in Table 2. The mean value of the N_u / N_p ratio is 1.06 with the corresponding COV of 0.235. It can be observed that the proposed N_p are able to provide reasonably good predictions for the concrete-filled high strength steel tubular X-joints, as shown in Figure 6. The validity ranges for the proposed design rules are $0.25 \leq b_1/b_0 \leq 0.93$, $12.6 \leq h_0/t_0 \leq 90.0$, $15.0 \leq b_0/t_0 \leq 90.0$ and $0.5 \leq h_0/b_0 \leq 2.5$, and most of these ranges are beyond the current limit of the CIDECT [1] design provisions.
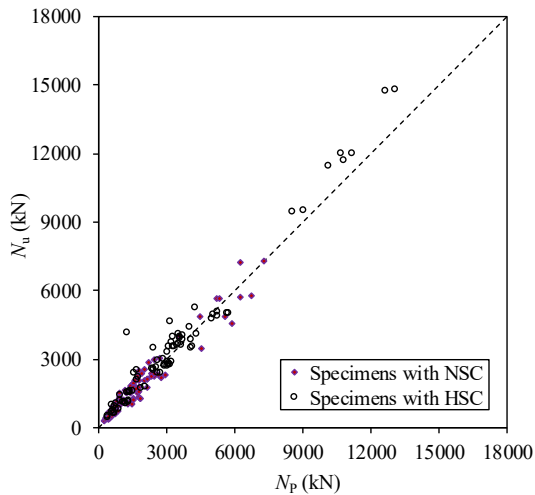
Fig. 6. Comparison of test and FE results with proposed design rules.

In addition, the test strengths (N_{1U}) of the 11 concrete-filled X-joint specimens reported by Packer [2] were also compared with the N_P calculated from Eq. (2). Note that the CIDECT [1] design provisions were developed based on these concrete-filled X-joint tests. The comparison of the N_{1U} and N_P are illustrated in Figure 7. It is shown that the proposed design rules are capable of providing conservative predictions for all the compression-loaded concrete-filled X-joint tests reported by Packer [2].
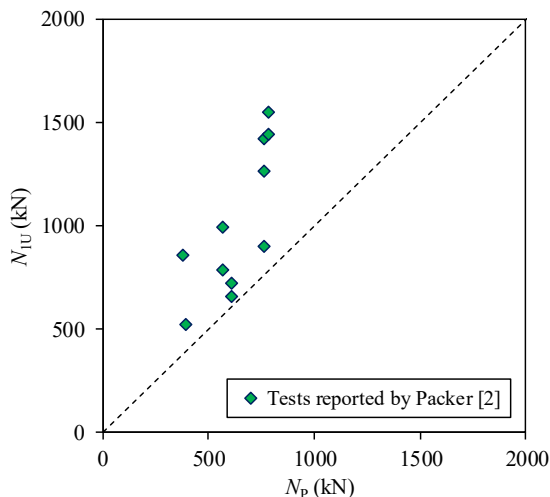

Fig. 7. Comparison of test strengths reported by Packer [2] with proposed nominal strengths.

6. Conclusions

In this paper, a numerical investigation was performed on concrete-filled high strength steel square and rectangular hollow section X-joints subjected to compression. The nominal yield

stresses of the steel tubes and the nominal cylinder strengths of the concrete infills were up to 900 and 100 MPa, respectively. A finite element (FE) model was developed and validated against the test results. On validation, a parametric study comprised 156 FE analyses was performed in order to generate further numerical data over a wide range of key parameters.

The ultimate strengths generated from the parametric study together with those from available tests were compared with the nominal strengths calculated from the CIDECT [1] design provisions. It has been shown that the CIDECT predictions exhibited significant scatter and were overly conservative for the X-joints with stocky tubular sections. In contrast, the CIDECT [1] overestimated the strengths of the concrete-filled high strength steel tubular X-joints when the chord sidewall slenderness values exceeded 50. Hence, new design rules have been proposed in this study for concrete-filled high strength steel tubular X-joints subjected to compression. It has been shown that the proposed design rules are able to provide reasonably good predictions.

Acknowledgement

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