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Flexural response of aluminium alloy SHS and RHS with internal stiffeners

Mei-Ni Su ¹, Ben Young ² and Leroy Gardner ³

Abstract

Tubular profiles, such as square and rectangular hollow sections (SHS and RHS) are widely used in a range of structural engineering applications. Their thin-walled nature means that local buckling is a key design concern, which is usually addressed by adhering to specified slenderness limits. An alternative approach is to employ local plate stiffeners, which can be practically achieved in extruded aluminium alloy sections through the introduction of internal cross stiffeners. The flexural behaviour and design of aluminium alloy SHS and RHS with internal stiffeners is the subject of investigation of the present paper. The primary aims of the study are to generate experimental and numerical data for these new types of cross-section in bending, as well as to assess the applicability of different approaches to their design at cross-sectional and system levels. First, an experimental investigation was performed on aluminium alloy SHS and RHS beams with internal stiffeners subjected to three-point bending, four-point bending and five-point bending (i.e. continuous beams over three supports) of three different configurations. Finite element (FE) models were also developed and validated against the presented test data. Once validated, the models were employed to generate additional data through numerical parametric studies. Comparisons are then made between the experimental/numerical capacities and the

design capacities predicted using international design specifications for aluminium alloy structures, as well as the continuous strength method (CSM). The design strengths predicted by the American and Australian/New Zealand specifications were found to be conservative, while improved predictions were achieved by Eurocode 9. The most accurate and consistent predictions were obtained using the CSM, which was able to capture the significant observed strain hardening at the cross-sectional level and moment redistribution at the global system level.

KEY WORDS: Aluminium alloys; Bending moment capacities; Continuous beams; Continuous strength method; Experimental investigation; Internal stiffeners; Numerical analyses; Simply supported beams; Square and rectangular hollow sections; Structural design; Testing

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1. Introduction

Aluminium alloys are used across a range of structural engineering applications, with square and rectangular hollow sections (SHS and RHS) being a popular cross-section shape. While SHS and RHS are commonly adopted, the extrusion process enables more complex shapes to be readily produced in aluminium alloys [1]. This can be particularly beneficial for enhancing resistance to local buckling through, for example, the addition of internal stiffeners. In this study, the flexural behaviour and ultimate bending capacity of square and rectangular hollow sections with internal cross stiffeners are investigated through experimentation and numerical modelling. The load-

deflection histories of the test specimens as well as the observed failure modes are reported. Further data are also generated through finite element modelling.

Investigations into the flexural behaviour of aluminium alloy beams have been carried out by many researchers in recent years – for both square and rectangular hollow section members [2-5] and thin-walled members with stiffeners [6-9] . To date, in light of the experimental and numerical results, the key aims of the present study are to investigate the importance of strain hardening and the applicability of plastic design to aluminium alloy structures, since previous research [10-13] has highlighted scope for improved design efficiency through consideration of these effects. Two different types of aluminium alloys - normal strength aluminium alloy 6063-T5 and high strength aluminium alloy 6061-T6, were examined to consider the influence of strain hardening on different tempers.

The use of continuity in a structural system can bring about benefits, such as increased load-carrying capacity and reduced deflections. Hence, the importance of moment redistribution in indeterminate aluminium alloy structures is considered herein through the study of two-span continuous beams. Theofanous et al. [14] reported that when considering moment redistribution in stainless steel continuous beams, the design capacities were found to be improved by around 10% and offer more accurate prediction of the test response. However, although structural design guidance is widely available for aluminium alloys, global plastic design is generally not permitted in international specifications such as the Aluminium Design Manual [15] and Australian/New Zealand Standards [16]. Eurocode 9 (EC9) [17] was the first code to allow full inelastic analysis of aluminium alloy structures [18], including the plastic hinge method in Annex H for continuous beams with Class 1 cross-sections. Available experimental data from the literature on

indeterminate aluminium alloy structures is rather limited, with the key studies being reported on continuous beams [19-21].

In this investigation, 6 three-point bending tests (to investigate the flexural response under a moment gradient), 5 four-point bending tests (to study the flexural response under uniform bending moment) and 19 continuous tests (to investigate moment redistribution and the ultimate load carrying capacities of indeterminate structures) have been conducted, and the results of 60 numerical simulations of simply supported beams and 90 simulations of continuous beams are presented. All tested and simulated specimens are aluminium alloy SHS and RHS with internal stiffeners. In the final part of this paper, the capacity predictions from three international aluminium alloy design specifications [15-17] are evaluated against the generated test and numerical data. A deformation-based design approach, the continuous strength method (CSM) [19, 22, 23], is also assessed. The CSM allows for moment redistribution as well as a systematic exploitation of strain hardening. The key findings of the comparisons are presented and discussed.

2. Experimental investigation

The experimental program comprised 6 three-point bending tests, 5 four-point bending tests and 19 five-point bending continuous beam tests. A series of different cross-section sizes, defined using the symbols illustrated in Figure 1, were examined. The cross-sectional dimensions shown in Table 1 are the average measured values for each test specimen in this study. The average measured material properties for each test specimen, determined following the testing procedure described in [24,25], are also presented in Table 1, where the following symbols are used: E is the Young's Modulus, f_y is the material yield stress (taken as the 0.2% proof stress), f_u is the material ultimate stress, ε_u is the strain corresponding to the ultimate tensile stress of the material and ε_f is the plastic strain corresponding to the material fracture.

The specimens were labelled according to the cross-sectional dimensions, type of material and the test configuration. For example, the label “+H50×95×10.5B3” defines an RHS with internal stiffeners of the same thickness as the outer walls of the section. In the label, the “+” refers to specimens with internal stiffeners, “H” means high strength aluminium alloy 6061-T6, with cross-sectional dimensions of width (50 mm) × height (95 mm) × thickness (10.5 mm). If the label has the letter “N”, it means the specimen is normal strength aluminium alloy 6063-T5. The symbol “B3” following the dimensions refers to the three-point bending tests, as shown in Figures 2 and 3, while the other configurations are indicated as “B4” for four-point bending (Figures 4 and 5) and “B5” for five-point bending (Figures 6 and 7). Meanwhile there are three different configurations for the five-point bending tests, which are signified as “B5I” for configuration I, “B5II” for configuration II and “B5III” for configuration III. If a test is repeated, a letter “R” is included at the end of the label.

For all specimens, steel bearing plates were placed between the test specimens and the rollers/half rounds at the loading and support points for the purpose of spreading the concentrated loads. Stiffening steel plates of 100 mm width and 10 mm thickness were also clamped to the webs of the relatively slender sections (+H95×95×4.3) at the loading points and the supports to prevent web crippling. A servo-controlled hydraulic testing machine was used to apply compressive force by displacement control to the specimens at a constant rate of 0.8 mm/min. A summary of the test results is given in Tables 2 and 3.

2.1 Three-point bending tests

In the three-point bending tests, the simply supported specimens were loaded at the mid-span, as shown in Figures 2 and 3. The beam span between the supports was 600 mm. One LVDT was used to measure the vertical deflection at mid-span and two LVDTs were placed at each end of the specimens to measure the end rotation.

Full moment-end rotation graphs obtained from the three-point bending tests are presented in Figure 8. Two specimens +H50×95×10.5B3 and +H95×50×10.5B3 failed by material yielding and inelastic local buckling, while the remainder of the specimens failed by tensile material fracture at mid-span (Figure 9). It should be noted that significant visual local buckling was not clearly apparent in the tests.

2.2 Four-point bending tests

In the four-point bending tests, the specimens were loaded symmetrically at two points through a spreader beam, as shown in Figures 4 and 5. The span of the beams was 900 mm, with the loads applied at third points. Three LVDTs were used to measure the vertical deflection of the beams at mid-span and at the loading points, respectively, in order to obtain the mid-span deflection and curvature in the constant moment region. Two further LVDTs were placed at each end of the beams to measure the end rotation.

Moment-curvature graphs obtained from the four-point bending tests are presented in Figure 10. Similar to three-point bending tests, specimens either failed by material yielding and inelastic local buckling or tensile material fracture at mid-span (Figure 11); meanwhile, no significant visual local buckling was observed during the tests.

During the bending tests, the internal cross stiffeners were shown to effectively impede local buckling of the compression flanges. As shown in Figure 12, the stiffeners acted as nodal lines, dividing the compression flange into two equal halves, resulting in a reduction in plate slenderness by a factor of two and an increase in load-bearing and deformation capacity.

2.3 Five-point bending tests

The overall nominal length of the continuous beams was 1690 mm. Three symmetrical five-point bending configurations were employed in this study. In loading configuration I, the distance between the loading points and the end supports (L_1) and the loading points and the central support (L_2) were all equal to 400 mm, while in the configurations II and III, the loads were applied at $L_2=266.7$ mm (i.e. the loads were at one third of the span from the central support) and $L_2=533.3$ mm (i.e. the loads were at two thirds of the span from the central support), respectively, as illustrated in Figure 6. The loading was applied at two points through a spreader beam (see Figure 7). Two LVDTs were used to measure the vertical deflection at the loading points. Two additional LVDTs were placed 150 mm either side of the mid-span, in order to estimate the mid-span rotation. Two further LVDTs were placed at each end of the beams to measure the end rotations.

The specimens failed principally by the formation of a plastic collapse mechanism comprising three plastic hinges and by material tensile fracture. For the loading configurations I and II, the first plastic hinge formed at the central support while the latter two plastic hinges formed at the loading points. In configuration III, the plastic hinges formed in the reverse sequence. Eventually all specimens fractured at the central support or at the loading points, though in some cases this was after the peak load had been attained. Significant local buckling was generally not visible in the test specimens. In all cases, the ultimate loads attained in the tests were found to be beyond

the theoretical loads corresponding to the occurrence of the first plastic hinge and the calculated plastic collapse loads. The load-deflection graphs for all five-point bending test specimens are presented in Figure 13, and a typical deformed specimen (+N95×50×10.5B5I) exhibiting three distinct plastic hinges is shown in Figure 14.

3. Numerical analyses

Numerical analyses were carried out in parallel with the experimental studies. The general purpose finite element (FE) package ABAQUS version 6.10 [26] was employed to simulate the beam experiments and to perform parametric investigations. The numerical parametric studies were conducted to assess the effect of key parameters, such as cross-section slenderness, cross-section aspect ratio and moment gradient on the strength, strain hardening and moment redistribution behaviour of aluminium alloy beams.

3.1 Numerical modelling approach and validation of models

The reduced integration four-noded doubly curved shell element S4R was employed in all FE models [27]., with a chosen mesh size of 10 mm × 10 mm Bearing plates were modelled using 10 mm thick solid elements. Hard contact in the normal direction and friction penalty contact (with the friction coefficient = 0.1) in the tangential direction were adopted between the solid plate (master surface) and the beam surface (slave surface). Simple support conditions were simulated by restraining the relevant degrees of freedom at the bottom flanges [28]. The beams were restrained longitudinally at the mid-span only. The material nonlinearity was included in the FE models by specifying sets of values of true stress and log plastic strain to define a piecewise linear response

The measured geometric and material properties from the test specimens were employed in the corresponding FE models for the validation study. Residual stresses were not measured in the experimental work and not explicitly modelled in the simulations [29-31]. Initial local geometric imperfections were included in the numerical models in the form of the lowest regular elastic local buckling mode shape, as obtained from linear eigenvalue buckling analyses. The initial local geometric imperfection amplitude was defined as 0.2 mm, which represented the average local imperfection amplitudes measured in the test specimens [32]. Nonlinear analyses of the models were carried out by means of the modified Riks procedure [26]. Since tensile material fracture was the governing failure mode for a number of the test specimens, tensile strains were monitored in the simulated beams, and the point of tensile fracture was defined as that when the maximum strain exceeds the material fracture strain ε_f obtained from tensile coupon tests; for cases where fracture occurred prior to the attainment of the peak load from the numerical model, this became the governing failure mode, as shown for the +N95×50×10.5B5I specimen in Figure 15.

The experimental and numerical ultimate resistances are compared in Tables 4 and 5, and may be seen to be in good overall agreement. The general shape of the moment-deflection curves from the FE models also matched closely those obtained from the experiments (Figure 15). The test failure modes were also well predicted by the FE models, where no significant local buckling was observed. Overall, it may be concluded that the FE models are able to capture accurately the experimentally observed structural behaviour of the aluminium alloy beams.

3.2 Numerical parametric studies

Upon validation of the developed numerical models, parametric studies were carried out, generating 60 numerical results for simply supported beams (Table 6) and 90 numerical results for continuous beams (Table 7). Both major and minor axis bending were modelled. The material

properties of a typical high strength aluminium alloy tube H64×64×3.0 (a specimen reported in [4] with $f_y = 233.8$ MPa and $f_u = 248.4$ MPa) and a typical normal strength aluminium alloy tube +N95×50×10.5 were employed in the models to represent high strength and normal strength aluminium alloys, respectively. A wide spectrum of aspect ratios b/h (0.28 - 3.62) and plate element width-to-thickness ratios b/t (3.40 – 26.50), covering the four cross-section classes, were considered in the parametric studies. Cross-sections with outer wall dimensions up to 180 mm and thickness up to 9.0 mm were modelled. The distance between the supports and the loading points varied from 400 mm to 900 mm.

4. Comparison of test and numerical results with design capacities

In this section, the experimental and numerical ultimate resistances, i.e. M_u for the simply supported beams and F_u for the continuous beams, are compared with the design strengths predicted using the American (M_{AA} or F_{AA}) [15], Australian/New Zealand ($M_{AS/NZS}$ or $F_{AS/NZS}$) [16] and European (M_{EC9} or F_{EC9}) [17] specifications for aluminium alloy structures, as shown in Tables 2, 3 and 8, as well as Figures 16-18. All comparisons made herein with EC9 (2007) use the more favourable Annex F approach for simply supported beams and Annex H approach for continuous beams. In addition, the predictions of the CSM (M_{csm} or F_{csm}) [19, 22, 23] are also evaluated against the experimental and numerical results. The comparisons were performed using the measured material properties and geometries, with all safety factors set equal to unity.

4.1 Simply supported beams (three-point and four-point bending)

The ultimate bending moments from the 11 experiments and 60 FE simulations on simply supported aluminium alloy beams are used herein to assess the accuracy of the four different design methods introduced above (the AA, the AS/NZS, EC9 and the CSM) [15-17, 19, 22, 23], as shown in Tables 2 and 8, as well as Figures 16 and 17.

4.1.1 International design specifications

There are a number of established international aluminium alloy structural design specifications. The American Aluminium Design Manual (AA) [15] provides design rules for aluminium alloy beams, in which a nominal weighted average design moment is determined as set out in Chapter F8.3 of Part I of the code. The design flexural capacity given in the Australia/New Zealand (AS/NZS) Standard [16] is the product of the elastic section modulus and a weighted average stress, determined on the basis of the stresses in the compressed portion of the section. Eurocode 9 [17] provides design rules for cross-section resistance in Section 6.2.5 of the code, but also presents an alternative method in Annex F for Class 1 sections, in which a correction factor $\alpha_{M,j}$ is adopted to take into account strain hardening. For the other cross-sections, EC9 defines the resistance as the yield stress f_y multiplied by the plastic modulus W_{pl} for Class 2 sections and by the elastic modulus W_{el} for Class 3 sections.

In comparison to the test and FE results for the simply supported beams, the predictions of the AA [15] and AS/NZS [16] are rather conservative, with mean values for M_u/M_{AA} and $M_u/M_{AS/NZS}$ of 1.40 and 1.66, respectively and corresponding coefficients of variation (COV) of 0.207 and 0.233. Meanwhile, EC9 [17], with Annex F applied to the Class 1 cross-sections yields more accurate predictions with a mean value of M_u/M_{EC9} of 1.27 and a COV of 0.150. The improved accuracy arising from the use of Annex F of EC9 [17] is due to the consideration of strain hardening for Class 1 sections..

4.1.2 Continuous strength method for determinate structures

The development and application of the continuous strength method (CSM) for the aluminium alloy flexural members have been described in previous studies [19, 22]. The CSM is a

deformation based design framework that allows for the beneficial influence of strain hardening for all non-slender cross-sections. The two main features of the CSM are: (1) a base curve defining a continuous relationship between local slenderness $\bar{\lambda}_p$ and cross-section deformation capacity; and (2) a strain hardening material model using a strain hardening modulus E_{sh} , as given in Eq. (1).

$$E_{sh} = \frac{f_u - f_y}{0.5\varepsilon_u - \varepsilon_y} \quad (1)$$

where the strain at the ultimate stress ε_u may be approximated from $\varepsilon_u = 0.13(1 - f_y / f_u) + 0.059$.

Following comparisons with the test and FE results, a mean value of test (or FE) to predicted CSM moment M_u/M_{csm} of 1.18 with a COV of 0.153 was obtained. Overall, the CSM approach provides the most accurate predictions of the bending capacity among the considered design approaches, with up to an approximately 50% improvement compared to the AS/NZS predictions. The results show that strain hardening plays an important role in the flexural capacities of aluminium alloy stocky sections, and that its influence can be effectively captured by the CSM [22].

4.2 Continuous beams (five-point bending)

The results of the 19 experiments and 90 numerical simulations on aluminium alloy continuous beams obtained in the present study are compared with the design capacities of the three international specifications [15-17] and the CSM [19] in order to assess their design accuracy for indeterminate aluminium alloy structural systems. The comparative results are summarized in Tables 3 and 8, and are also plotted in Figure 18.

4.2.1 International design specifications

The AA (F_{AA}) [15] and AS/NZS ($F_{AS/NZS}$) [16] design methods use elastic global analysis and the predicted failure loads of the continuous beams are determined when the most heavily loaded cross-section reaches its ultimate resistance. However, the approaches and parameters that are used to calculate the cross-section resistance are different in the two specifications, as outlined in the previous section. According to EC9 [17], the plastic hinge method in Annex H applies principally to Class 1 sections only, but can be also used for Class 2 and 3 sections provided specific account of the effects of local buckling are taken into consideration. In this study, the plastic hinge method (F_{EC9}) is only applied to Class 1 cross-sections, while global elastic analysis is used for specimens of other cross-section classes. Further details may be found in Su et al. [19].

The mean values of the ultimate load to predicted resistances ratios for the three design specifications, F_u/F_{AA} , $F_u/F_{AS/NZS}$ and F_u/F_{EC9} are 1.70, 2.02 and 1.37, with corresponding COVs of 0.251, 0.276 and 0.178, respectively. Among the considered specifications, the AS/NZS [16] specification provides the most conservative predictions, while the EC9 [17] provisions yield the most accurate predictions. Overall, the predictions of all three specifications are rather conservative, particularly for the more stocky cross-sections, as shown in Figure 18. The comparisons indicate that the accuracy of the plastic hinge method stems from the consideration of both plastic global analysis (i.e. moment redistribution) and strain hardening.

4.2.2 Continuous strength method

The continuous strength method (CSM) [19] for indeterminate structures combines the merits of traditional plastic analysis, considering the formation of a plastic collapse mechanism as the failure condition, and an accurate assessment of the cross-section moment capacity, allowing for strain hardening. Besides the two key components of the CSM as mentioned in Section 4.1.2,

another key diversion of the CSM from the plastic hinge method is the theoretical cross-section strain ratios at the hinges being proportional to the hinge rotation ratios (i.e. the capacity is related to the strain demand), as described in [19]

The comparison of the test and numerical results with the CSM predictions reveal a mean value of F_u/F_{csm} of 1.25 and a COV of 0.165. The CSM [19] for indeterminate structures provides the most precise predictions of the test and numerical results, with the mean strength prediction ratios being closest to unity and the COV being the lowest, by allowing moment redistribution and accounting for strain hardening in the calculation of cross-section resistance.

5. Conclusions

A total of 30 aluminium alloy beams of square and rectangular hollow sections with internal cross stiffeners, subjected to three-point bending, four-point bending and five-point bending, have been tested in this study. The specimens were Class 1 sections according to Eurocode 9. Numerical analyses were also performed to supplement the experimental programme, through the generation of 150 parametric results. The combined data set of experimental and numerical results was used to assess the accuracy of three international design specifications: the Aluminium Design Manual, the Australian/New Zealand Standard and Eurocode 9 as well as the continuous strength method (CSM). The results revealed that the three current design specifications underestimate the ultimate capacity of both simply supported beams and continuous beams with hollow cross-sections and internal stiffeners. However, the CSM, which considers strain hardening at the cross-section level and moment redistribution at the global system level, was shown to provide accurate and consistent strength predictions for aluminium alloy square and rectangular hollow sections with internal stiffeners. Thus, it is recommended to use the Continuous Strength Method in the design of aluminium alloy stiffened SHS and RHS structural members.

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Notation

B	= Section width
b	= Flat width of flange
E	= Young's modulus
E_{sh}	= Strain hardening modulus
f_y	= Yield strength, taken as the 0.2% proof stress
f_u	= Ultimate tensile strength
F_{AA}	= Ultimate load predicted by the AA
$F_{AS/NZS}$	= Ultimate load predicted by the AS/NZS
F_{csm}	= Ultimate load predicted by the CSM
F_{design}	= Ultimate load predicted by different design methods
F_{EC9}	= Ultimate load predicted by the plastic hinge method in Annex H of EC9
F_{exp}	= Experimental ultimate load
F_{FE}	= Ultimate load obtained from FE models
F_u	= Experimental and numerical ultimate load
H	= Section height

h	= Flat height of web
L	= Member length
M_{AA}	= Ultimate moment capacity predicted by the AA
$M_{AS/NZS}$	= Ultimate moment capacity predicted by the AS/NZS
M_{csm}	= Ultimate moment capacity predicted by the CSM
M_{design}	= Ultimate moment capacity predicted by different design methods
M_{EC9}	= Ultimate moment capacity predicted by Annex F of EC9
M_{exp}	= Experimental ultimate moment
M_{FE}	= Ultimate moment obtained from FE models
M_u	= Ultimate moment obtained from either test or FE models
t	= Wall thickness
W_{eff}	= Elastic modulus of effective section
W_{el}	= Elastic section modulus
W_{pl}	= Plastic section modulus
ε_f	= Material fracture strain
ε_u	= Strain at ultimate tensile stress
$\bar{\lambda}_p$	= Cross-section/plate slenderness ($=\sqrt{f_y/\sigma_{cr}}$)
σ_{cr}	= Elastic buckling stress

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Table 1. Measured specimen dimensions and material properties obtained from the tensile coupon tests

Specimen	B (mm)	H (mm)	t (mm)	E (GPa)	f_y (MPa)	f_u (MPa)	ε_u (%)	ε_f (%)
+H50×95×10.5B3	49.7	94.7	10.35	70	199	218	4.7	11.0
+H95×50×10.5B3	94.6	49.8	10.30	70	199	218	4.7	11.0
+H70×120×10.5B3	69.8	119.9	10.28	70	192	222	8.5	11.2
+H120×70×10.5B3	119.9	69.8	10.32	70	192	222	8.5	11.2
+H95×95×4.3B3	95.2	95.1	4.13	67	228	240	6.0	6.4
+H95×95×4.3B3-R	95.2	95.3	4.17	67	228	240	6.0	6.4
+H70×120×10.5B4	69.9	119.9	10.30	70	192	222	8.5	11.2
+H120×70×10.5B4	120.0	69.9	10.31	69	210	238	4.6	6.5
+H95×95×4.3B4	95.3	95.2	4.16	66	228	236	6.0	7.7
+N50×95×10.5B4	49.7	94.6	10.13	72	122	186	9.9	17.0
+N95×50×10.5B4	94.6	49.7	10.08	72	122	186	9.9	17.0
+H50×95×10.5B5I	49.9	94.7	10.33	70	199	218	4.7	11.0
+H95×50×10.5B5I	94.8	49.9	10.35	70	199	218	4.7	11.0
+H70×120×10.5B5I	69.9	120.0	10.30	70	192	222	8.5	11.2
+H120×70×10.5B5I	120.0	70.0	10.30	70	192	222	8.5	11.2
+H95×95×4.3B5I	95.3	95.2	4.17	66	228	236	6.0	7.7
+H95×95×4.3B5I-R	95.2	95.2	4.14	67	228	240	6.0	6.4
+N50×95×10.5B5I	49.7	94.6	10.28	68	151	181	9.6	14.7
+N95×50×10.5B5I	94.7	49.7	10.27	68	151	181	9.6	14.7
+H50×95×10.5B5II	49.7	94.6	10.26	70	199	218	4.7	11.0
+H70×120×10.5B5II	69.9	120.0	10.26	70	192	222	8.5	11.2
+H120×70×10.5B5II	120.0	69.9	10.33	70	192	222	8.5	11.2
+H95×95×4.3B5II	95.3	95.2	4.17	67	228	240	6.0	6.4
+H95×95×4.3B5II-R	95.2	95.2	4.15	66	228	236	6.0	7.7
+N95×50×10.5B5II	94.6	49.7	10.31	68	151	181	9.6	14.7
+H50×95×10.5B5III	49.76	94.7	10.29	70	199	218	4.7	11.0
+H70×120×10.5B5III	69.94	120.0	10.25	69	210	238	4.6	6.5
+H120×70×10.5B5III	120.07	69.9	10.35	69	215	229	7.5	10.7
+H95×95×4.3B5III	95.27	95.2	4.15	69	208	238	7.0	9.5
+H95×95×4.3B5III-R	95.14	95.3	4.16	67	228	240	6.0	6.4

Table 2. Comparison between simply supported bending test results and design capacities

Specimen	$\bar{\lambda}_p$	M_{exp} (kNm)	$\frac{M_{exp}}{M_{AA}}$	$\frac{M_{exp}}{M_{AS/NZS}}$	$\frac{M_{exp}}{M_{EC9}}$	$\frac{M_{exp}}{M_{csm}}$
+H50×95×10.5B3	0.05	26.7	1.67	2.20	1.51	1.46
+H95×50×10.5B3	0.12	13.6	1.51	2.01	1.41	1.37
+H70×120×10.5B3	0.08	45.7	1.64	2.08	1.44	1.37
+H120×70×10.5B3	0.14	26.9	1.54	1.93	1.39	1.32
+H95×95×4.3B3	0.30	16.5	1.29	1.49	1.21	1.17
+H95×95×4.3B3-R	0.30	17.1	1.32	1.53	1.23	1.19
+H70×120×10.5B4	0.08	38.2	1.37	1.74	1.20	1.14
+H120×70×10.5B4	0.15	22.0	1.15	1.45	1.05	1.00
+H95×95×4.3B4	0.30	14.9	1.15	1.33	1.11	1.06
+N50×95×10.5B4	0.04	17.6	1.82	2.40	1.52	1.45
+N95×50×10.5B4	0.09	8.4	1.55	2.06	1.34	1.27
Mean			1.46	1.84	1.31	1.25
COV			0.149	0.191	0.122	0.122

Table 3. Comparison between five-point bending test results and design capacities

Specimen	$\bar{\lambda}_p$	F_{exp} (kN)	$\frac{F_{exp}}{F_{AA}}$	$\frac{F_{exp}}{F_{AS/NZS}}$	$\frac{F_{exp}}{F_{EC9}}$	$\frac{F_{exp}}{F_{csm}}$
+H50×95×10.5B5I	0.02	128.1	1.93	2.58	1.74	1.50
+H95×50×10.5B5I	0.10	220.9	1.78	2.37	1.65	1.44
+H70×120×10.5B5I	0.04	678.4	1.79	2.27	1.45	1.33
+H120×70×10.5B5I	0.11	416.3	1.74	2.18	1.44	1.32
+H95×95×4.3B5I	0.26	250.4	1.46	1.69	1.33	1.19
+H95×95×4.3B5I-R	0.26	250.6	1.43	1.65	1.26	1.14
+N50×95×10.5B5I	0.02	329.6	2.00	2.66	1.58	1.48
+N95×50×10.5B5I	0.09	171.1	1.84	2.45	1.51	1.42
+H50×95×10.5B5II	0.02	438.9	2.05	2.75	1.49	1.31
+H70×120×10.5B5II	0.04	922.7	2.38	3.02	1.56	1.46
+H120×70×10.5B5II	0.11	530.4	2.19	2.75	1.48	1.38
+H95×95×4.3B5II	0.25	319.4	1.84	2.13	1.31	1.20
+H95×95×4.3B5II-R	0.26	326.0	1.84	2.13	1.35	1.22
+N95×50×10.5B5II	0.09	199.1	2.16	2.88	1.56	1.37
+H50×95×10.5B5III	0.01	358.4	1.56	2.09	1.51	1.32
+H70×120×10.5B5III	0.02	708.2	1.62	2.05	1.53	1.34
+H120×70×10.5B5III	0.12	420.2	1.49	1.87	1.51	1.32
+H95×95×4.3B5III	0.24	274.3	1.61	1.86	1.44	1.33
+H95×95×4.3B5III-R	0.25	253.4	1.36	1.58	1.30	1.19
Mean			1.80	2.27	1.48	1.33
COV			0.152	0.185	0.084	0.077

Table 4. Comparison between experimental and numerical results of simply supported beams

Specimen	M_{exp} (kNm)	M_{FE} (kNm)	$\frac{M_{exp}}{M_{FE}}$
+H50×95×10.5B3	26.7	24.7	1.08
+H95×50×10.5B3	13.6	13.5	1.01
+H70×120×10.5B3	45.7	43.1	1.06
+H120×70×10.5B3	26.9	26.7	1.00
+H95×95×4.3B3	16.5	16.4	1.00
+H95×95×4.3B3-R	17.1	16.8	1.02
+H70×120×10.5B4	38.2	37.8	1.01
+H120×70×10.5B4	22.0	21.4	1.03
+H95×95×4.3B4	14.9	14.3	1.04
+N50×95×10.5B4	17.6	18.7	0.94
+N95×50×10.5B4	8.4	7.8	1.08
		Mean	1.02
		COV	0.039

Table 5. Comparison between experimental and numerical results of continuous beams

Specimen	F_{exp} (kN)	F_{FE} (kN)	$\frac{F_{exp}}{F_{FE}}$
+H50×95×10.5B5I	423.8	377.8	1.12
+H95×50×10.5B5I	220.9	212.1	1.04
+H70×120×10.5B5I	678.4	680.4	1.00
+H120×70×10.5B5I	416.3	415.0	1.00
+H95×95×4.3B5I	250.4	239.1	1.05
+H95×95×4.3B5I-R	250.6	244.9	1.02
+N50×95×10.5B5I	329.6	328.7	1.00
+N95×50×10.5B5I	171.1	178.4	0.96
+H50×95×10.5B5II	438.9	431.5	1.02
+H70×120×10.5B5II	922.7	871.5	1.05
+H120×70×10.5B5II	530.4	535.3	1.00
+H95×95×4.3B5II	319.4	326.7	0.98
+H95×95×4.3B5II-R	326.0	310.1	1.05
+N95×50×10.5B5II	199.1	218.1	0.91
+H50×95×10.5B5III	358.4	317.3	1.13
+H70×120×10.5B5III	708.2	655.7	1.08
+H120×70×10.5B5III	420.2	402.0	1.04
+H95×95×4.3B5III	274.3	253.3	1.08
+H95×95×4.3B5III-R	253.4	232.5	1.09
		Mean	1.03
		COV	0.052

Table 6. Ultimate loads of simulated simply supported beams generated from the parametric studies

Specimen	F_{FE} (kN)	Specimen	F_{FE} (kN)
+H180×180×9.0B3	120.3	+H180×180×9.0B4	116.6
+H180×180×6.0B3	78.4	+H180×180×6.0B4	75.7
+H180×180×3.5B3	42.2	+H180×180×3.5B4	40.6
+H160×200×9.0B3	131.6	+H160×200×9.0B4	123.2
+H160×200×6.0B3	90.6	+H160×200×6.0B4	84.4
+H160×200×3.5B3	50.3	+H160×200×3.5B4	46.4
+H140×100×6.5B3	35.9	+H140×100×6.5B4	30.4
+H140×100×5.0B3	28.0	+H140×100×5.0B4	23.2
+H140×100×2.5B3	13.5	+H140×100×2.5B4	12.0
+H130×50×6.5B3	12.6	+H130×50×6.5B4	11.0
+H130×50×5.0B3	10.4	+H130×50×5.0B4	8.6
+H130×50×2.5B3	5.1	+H130×50×2.5B4	4.5
+H50×130×6.5B3	31.8	+H50×130×6.5B4	27.5
+H50×130×5.0B3	25.0	+H50×130×5.0B4	21.5
+H50×130×2.5B3	11.9	+H50×130×2.5B4	10.7
+N180×180×9.0B3	84.2	+N180×180×9.0B4	80.1
+N180×180×6.0B3	51.7	+N180×180×6.0B4	49.0
+N180×180×3.5B3	25.6	+N180×180×3.5B4	22.9
+N160×200×9.0B3	93.3	+N160×200×9.0B4	78.9
+N160×200×6.0B3	65.0	+N160×200×6.0B4	55.0
+N160×200×3.5B3	31.2	+N160×200×3.5B4	28.4
+N140×100×6.5B3	26.8	+N140×100×6.5B4	19.2
+N140×100×5.0B3	20.4	+N140×100×5.0B4	14.5
+N140×100×2.5B3	8.1	+N140×100×2.5B4	6.9
+N130×50×6.5B3	8.5	+N130×50×6.5B4	6.5
+N130×50×5.0B3	6.5	+N130×50×5.0B4	5.1
+N130×50×2.5B3	3.3	+N130×50×2.5B4	2.7
+N50×130×6.5B3	23.6	+N50×130×6.5B4	18.5
+N50×130×5.0B3	18.3	+N50×130×5.0B4	14.6
+N50×130×2.5B3	7.9	+N50×130×2.5B4	7.2

Table 7. Ultimate loads of simulated continuous beams generated from the parametric studies

Specimen	F_{FE} (kN)	Specimen	F_{FE} (kN)	Specimen	F_{FE} (kN)
+H180×180×9.0 B5I	860.0	+H180×180×9.0 B5II	1030.0	+H180×180×9.0 B5III	797.4
+H180×180×6.0 B5I	561.1	+H180×180×6.0 B5II	634.5	+H180×180×6.0 B5III	512.7
+H180×180×3.5 B5I	307.0	+H180×180×3.5 B5II	318.1	+H180×180×3.5 B5III	262.2
+H160×200×9.0 B5I	930.1	+H160×200×9.0 B5II	1061.0	+H160×200×9.0 B5III	863.5
+H160×200×6.0 B5I	604.9	+H160×200×6.0 B5II	641.3	+H160×200×6.0 B5III	556.0
+H160×200×3.5 B5I	309.7	+H160×200×3.5 B5II	307.8	+H160×200×3.5 B5III	262.7
+H140×100×6.5 B5I	340.5	+H140×100×6.5 B5II	451.4	+H140×100×6.5 B5III	344.2
+H140×100×5.0 B5I	260.0	+H140×100×5.0 B5II	331.1	+H140×100×5.0 B5III	251.0
+H140×100×2.5 B5I	119.9	+H140×100×2.5 B5II	158.9	+H140×100×2.5 B5III	120.7
+H130×50×6.5 B5I	201.7	+H130×50×6.5 B5II	265.5	+H130×50×6.5 B5III	192.1
+H130×50×5.0 B5I	157.1	+H130×50×5.0 B5II	206.7	+H130×50×5.0 B5III	149.7
+H130×50×2.5 B5I	77.4	+H130×50×2.5 B5II	100.3	+H130×50×2.5 B5III	72.5
+H50×130×6.5 B5I	463.5	+H50×130×6.5 B5II	627.2	+H50×130×6.5 B5III	485.0
+H50×130×5.0 B5I	344.2	+H50×130×5.0 B5II	452.8	+H50×130×5.0 B5III	364.8
+H50×130×2.5 B5I	159.8	+H50×130×2.5 B5II	197.0	+H50×130×2.5 B5III	156.6
+N180×180×9.0 B5I	529.8	+N180×180×9.0 B5II	644.4	+N180×180×9.0 B5III	499.2
+N180×180×6.0 B5I	325.3	+N180×180×6.0 B5II	373.1	+N180×180×6.0 B5III	295.0
+N180×180×3.5 B5I	154.1	+N180×180×3.5 B5II	177.4	+N180×180×3.5 B5III	164.7
+N160×200×9.0 B5I	564.1	+N160×200×9.0 B5II	669.2	+N160×200×9.0 B5III	524.9
+N160×200×6.0 B5I	347.4	+N160×200×6.0 B5II	394.4	+N160×200×6.0 B5III	342.0
+N160×200×3.5 B5I	144.6	+N160×200×3.5 B5II	174.6	+N160×200×3.5 B5III	170.5
+N140×100×6.5 B5I	238.3	+N140×100×6.5 B5II	312.6	+N140×100×6.5 B5III	245.6
+N140×100×5.0 B5I	177.3	+N140×100×5.0 B5II	222.8	+N140×100×5.0 B5III	170.2
+N140×100×2.5 B5I	76.9	+N140×100×2.5 B5II	102.8	+N140×100×2.5 B5III	80.8
+N130×50×6.5 B5I	141.1	+N130×50×6.5 B5II	175.9	+N130×50×6.5 B5III	132.4
+N130×50×5.0 B5I	108.0	+N130×50×5.0 B5II	138.0	+N130×50×5.0 B5III	103.1
+N130×50×2.5 B5I	50.9	+N130×50×2.5 B5II	65.8	+N130×50×2.5 B5III	51.3
+N50×130×6.5 B5I	340.1	+N50×130×6.5 B5II	450.4	+N50×130×6.5 B5III	358.6
+N50×130×5.0 B5I	233.1	+N50×130×5.0 B5II	327.2	+N50×130×5.0 B5III	269.4
+N50×130×2.5 B5I	104.2	+N50×130×2.5 B5II	120.9	+N50×130×2.5 B5III	104.7

Table 8. Summary of comparisons between bending test and numerical results with design strengths

	Simply Supported Beams				Continuous Beams			
	$\frac{M_u}{M_{AA}}$	$\frac{M_u}{M_{AS/NZS}}$	$\frac{M_u}{M_{EC9}}$	$\frac{M_u}{M_{csm}}$	$\frac{F_u}{F_{AA}}$	$\frac{F_u}{F_{AS/NZS}}$	$\frac{F_u}{F_{EC9}}$	$\frac{F_u}{F_{csm}}$
Number of specimens	71				109			
Mean	1.40	1.66	1.27	1.18	1.70	2.02	1.37	1.25
COV	0.207	0.233	0.150	0.153	0.251	0.276	0.178	0.165

Figure 1. Definition of symbols for SHS/RHS with internal stiffeners having all elements of same thickness

Figure 2. Schematic illustration of three-point bending test configuration (dimensions in mm)

Figure 3. Experimental setup for three-point bending test

Figure 4. Schematic illustration of four-point bending test configuration (dimensions in mm)

Figure 5. Experimental setup for four-point bending test

Figure 6. Schematic illustration of five-point bending configuration (dimensions in mm)

Figure 7. Experimental setup for five-point bending test

Figure 8. Moment-end rotation curves obtained from three-point bending tests

Figure 9. Tested and numerical three-point bending beams ($+H70 \times 120 \times 10.5B3$)

Figure 10. Moment–curvature curves obtained from four-point bending tests

Figure 11. Tested and numerical four-point bending beams (+N95×50×10.5B4)

Figure 12. Tested four-point bending beams after cutting in the mid-span (+H95×595×4.3B4)

Figure 13. Load–deflection curves obtained from five-point bending tests

Figure 14. Tested and numerical five-point bending beams (+N95×50×10.5B5I)

Figure 15. Experimental and numerical load-displacement curves for specimen

Figure 16. Comparison of three-point bending experimental and numerical results with design strengths

Figure 17. Comparison of four-point bending experimental and numerical results with design strengths

(a) Configuration I

(b) Configuration II

(c) Configuration III

Figure 18. Comparison of five-point bending experimental and numerical results with design strengths