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1 **Bending-Shear Interaction of Cold-Formed Stainless Steel Lipped**
2 **Channel Sections**

3
4 **D. M. M. P. Dissanayake**

5 Faculty of Engineering and Environment, University of Northumbria,
6 Newcastle, UK.

7 **K. Poologanathan**

8 Faculty of Engineering and Environment, University of Northumbria,
9 Newcastle, UK.

10 **S. Gunalan**

11 School of Engineering and Built Environment, Griffith University,
12 Gold Coast, Australia.

13 **K. D. Tsavdaridis**

14 School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of
15 Leeds, UK.

16 **K. S. Wanniarachchi**

17 Faculty of Engineering, University of Ruhuna, Sri Lanka.

18 **B. Nagaratnam**

19 Faculty of Engineering and Environment, University of Northumbria,
20 Newcastle, UK.

21
22 **Abstract**

23 The bending-shear interaction response of cold-formed stainless steel lipped channel sections
24 has been given inadequate attention in the past. Therefore, this paper investigates the bending
25 and shear interaction behaviour of cold-formed stainless steel lipped channel sections using
26 numerical studies. Finite element (FE) models were developed and validated against the
27 experimental results found in the literature for three-point and four-point loading tests of lipped
28 channel sections of both cold-formed stainless steel and cold-formed steel. The elaborated FE
29 results were used for a comprehensive parametric study that was conducted comprising 60 FE
30 models of three-point loading simulations of stainless steel lipped channels with five different
31 aspect ratios to study the shear response and the bending-shear interaction response. Another
32 12 FE models of four-point bending simulations were developed to study the bending response.

33 The numerical results were analysed and it was found that the sections with aspect ratios of 1.5
34 and 2.0 are subjected to the interaction of bending and shear while there is no interaction effect
35 observed in the sections with other aspect ratios. Eurocode 3 and American specifications
36 interaction equations were then evaluated using the numerical results. These design provisions
37 are found to be too conservative for a higher level of applied shear force. Therefore, revised
38 design equations for bending and shear interaction were proposed aiming better prediction
39 accuracy. Further, a statistical evaluation was conducted for the proposed interaction equations
40 and results suggested improved and consistent predictions.

41 *Keywords: Lipped channel beams, Cold-formed stainless steel, Bending-shear interaction,*
42 *Numerical modelling, Eurocode 3, American specifications, Design rules*

43 **1 Introduction**

44 Lipped channel beam (LCB) sections have commonly been used as load-bearing components
45 such as roof purlins, wall studs, and floor joists in the structural applications. In practice, a
46 higher level of stresses is developed within the cross-sections, due to the interaction of the
47 bending and shear actions prevalent, in particular, at the supports of continuous spans and
48 cantilever beams. The bending and shear resistances of a section tend to reduce under the
49 bending-shear interaction, thus it is worth investigating this bending-shear interaction in the
50 structural design process. The interaction of the bending and shear actions of hot-rolled, plate
51 girder and cold-formed sections has been the motive for a number of investigations conducted
52 over the years. The initial experiments on stainless steel plate girders have been performed by
53 Olsson [1] while Real et al. [2] conducted both testing and numerical modelling of stainless
54 steel plate girders to study the shear response. The bending-shear interaction behaviour of
55 stainless steel plate girders have been investigated by Saliba and Gardner [3] and Chen et al.
56 [4] using experimental and numerical studies. Sinur and Beg [5],[6] have also carried out both
57 experimental and numerical studies on stiffened carbon steel plate girders. In addition, a
58 number of studies have been performed on cold-formed steel sections. Keerthan and
59 Mahendran [7] experimented the bending-shear interaction behaviour of cold-formed steel
60 lipped channel sections, while, Pham and Hancock [8] performed both experimental and
61 numerical studies. Furthermore, the bending-shear interaction behaviour of cold-formed steel
62 hollow flange channel sections has been studied by Keerthan et al. [9]. However, no
63 comprehensive investigation has been conducted for cold-formed stainless steel lipped channel

64 sections in the context of bending and shear interaction behaviour. Therefore, this gap in the
65 literature was covered in this study.

66 Most of the design provisions for bending-shear interaction have been based on the resistance
67 model first proposed by Basler [10]. Basler [10] investigated the bending-shear interaction of
68 longitudinally unstiffened plate girders with slender webs and proposed a mechanical model
69 considering the effect of interaction. This model includes the post-buckling effects of slender
70 webs and is given by Eq. (1).

$$71 \left(\frac{V}{V_w}\right)^2 + \frac{M-M_f}{M_p-M_f} = 1 \text{ for } M_f < M < M_{\text{eff}} \quad (1)$$

72 where V_w is the web shear capacity, M_f is the bending capacity of flanges alone, M_p is the
73 plastic bending capacity of the whole section, M_{eff} is the bending capacity of the effective cross-
74 section, and V and M are the design shear force and design bending moment, respectively.

75 In this resistance model for bending-shear interaction, it is assumed that when the applied
76 bending moment is less than the flange bending resistance, the applied bending moment is
77 resisted solely by the flanges, therefore, no reduction occurs in the shear capacity of the webs.
78 However, when the sections are subjected to higher moments than the flange bending
79 resistance, a part of the section moment is transferred to the section webs and therefore, the
80 web shear resistance begins to reduce. Thus, the interaction of bending and shear actions has
81 to be considered.

82 In the current version of European standards for stainless steel (EN1993-1-4 [11]), no
83 provisions have been made for the bending and shear interaction. This is because, EN1993-1-
84 4 [11] provides only the supplementary provisions for stainless steel and therefore, European
85 standards for cold-formed steel (EN1993-1-3 [12]) and European standards for plated steel
86 (EN1993-1-5 [13]) are to be referred for the bending and shear interaction design of stainless
87 steel cold-formed and plated sections, respectively. These interaction provisions are based on
88 a modified version of Basler's [10] resistance model.

89 Bleich [14] has investigated the bending-shear interaction response of rectangular plates and
90 proposed a circular interaction equation. This is expressed in Eq. (2). This was found to be
91 conservative for sections with transverse stiffeners. Therefore, Shahabian and Roberts [15]
92 have suggested a rounded interaction equation and is given by Eq. (3). Moreover, LaBoube and

93 Yu [16] have conducted experiments on the bending-shear interaction behaviour of cold-
94 formed steel lipped channel sections without transverse stiffeners. Based on their work,
95 LaBoube and Yu [16] have also proposed a relationship for the bending-shear interaction.
96 Modified versions of some of these interaction equations have been the basis for the bending
97 and shear interaction design provisions in American specifications for cold-formed stainless
98 steel design, SEI/ASCE 8-02 [17].

$$99 \left(\frac{M}{M_n}\right)^2 + \left(\frac{V}{V_n}\right)^2 \leq 1.0 \quad (2)$$

$$100 \left(\frac{M}{M_n}\right)^4 + \left(\frac{V}{V_n}\right)^4 \leq 1.0 \quad (3)$$

101 where M_n and V_n are nominal bending strength and nominal shear strength of the section,
102 respectively.

103 This paper presents the details of numerical investigations carried out to study the bending-
104 shear interaction behaviour of cold-formed stainless steel lipped channel sections. First, a
105 summary of codified design provisions for bending-shear interaction is discussed. Then, the
106 details of developing the finite element (FE) models and the validation study are outlined.
107 Thereafter, the results of the comprehensive parametric study conducted are presented. Finally,
108 the analysis of numerical results, assessment of available design provisions, and suggested
109 modifications to them in the context of bending-shear interaction of stainless steel LCBs are
110 elaborated.

111 **2 Review of design rules**

112 In this section, design provisions for bending and shear interaction found in European standards
113 and American specifications are discussed.

114 **2.1 Eurocode 3 design provisions**

115 In the absence of provisions for bending and shear interaction, European standards for stainless
116 steel (EN1993-1-4 [11]) refers to the provisions given in European standards for cold-formed
117 steel (EN1993-1-3 [12]) for the bending-shear interaction design of stainless steel cold-formed
118 sections. Interaction equation provided in EN1993-1-3 [12] is based on Basler's [10] resistance
119 model and is given by Eq. (4). This interaction model is valid only when the applied shear force
120 (V_{Ed}) is greater than 50 % of the web shear resistance ($V_{w,Rd}$) and when the applied moment

121 ($M_{y,Ed}$) exceeds the bending resistance corresponding to the effective areas of flanges alone
 122 ($M_{f,Rd}$).

$$123 \frac{M_{y,Ed}}{M_{y,Rd}} + \left(1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right) \left(\frac{2V_{Ed}}{V_{w,Rd}} - 1\right)^2 \leq 1.0 \quad (4)$$

124 where $M_{y,Rd}$ is the bending resistance and $M_{pl,Rd}$ is the plastic bending resistance of the section.

125 For the calculation of bending resistance consisting of the effective flange area ($M_{f,Rd}$) and the
 126 plastic bending resistance of the section ($M_{pl,Rd}$), provisions given in EN1993-1-5 [13] should
 127 be referred. This includes the calculation of the effective widths of plate elements according to
 128 the effective width method to account for the loss of effectiveness due to the local buckling.
 129 The cross-section bending resistance ($M_{y,Rd}$) can be calculated using Eq. (5) based on effective
 130 cross-section properties according to EN1993-1-4 [11].

$$131 M_{y,Rd} = M_{eff,Rd} = \frac{W_{y,eff} f_y}{\gamma_{M0}} \quad (5)$$

132 where $W_{y,eff}$ is the effective section modulus, f_y is the yield strength, and γ_{M0} is the partial factor
 133 for cross section resistance.

134 The rotated stress field theory proposed by Höglund [18] has been adopted in European
 135 standards for stainless steel (EN1993-1-4 [11]) to calculate section shear resistance. However,
 136 for the bending-shear interaction calculation, only the web contribution to shear resistance
 137 ($V_{w,Rd}$) is considered and this is given by Eq. (6).

$$138 V_{w,Rd} = \frac{\chi_w f_{yw} h_w t_w}{\sqrt{3} \gamma_{M1}} \quad (6)$$

139 where χ_w is the web shear buckling reduction factor which is a function of web slenderness
 140 ($\bar{\lambda}_w$), f_{yw} is the yield strength, h_w is the web height, t_w is the web thickness, and γ_{M1} is the
 141 partial factor for member resistance. Table 1 gives the set of equations provided in EN1993-1-
 142 4 [11] for the web shear buckling reduction factor (χ_w) of the sections with rigid end posts.
 143 Dissanayake et al. [19] has modified this set of expressions for web shear buckling reduction
 144 factor (χ_w) considering cold-formed stainless steel lipped channel sections and those are given
 145 in Table 2.

146

147 Table 1 Web shear buckling reduction factor (χ_w) of EN1993-1-4 [11] for the sections with rigid end post.

χ_w	
$\bar{\lambda}_w \leq 0.65/\eta$	η
$0.65/\eta < \bar{\lambda}_w < 0.65$	$0.65/\bar{\lambda}_w$
$\bar{\lambda}_w \geq 0.65$	$1.56/(0.91 + \bar{\lambda}_w)$

148

149 Table 2 Proposed expressions of web shear buckling reduction factor (χ_w) for the sections with rigid end post by
150 Dissanayake et al. [19].

χ_w	
$\bar{\lambda}_w \leq 0.12$	2.1
$0.12 < \bar{\lambda}_w < 0.667$	$0.839/\bar{\lambda}_w^{0.433}$
$\bar{\lambda}_w \geq 0.667$	$1.797/(1.13 + \bar{\lambda}_w)$

151

152 2.2 American specifications, SEI/ASCE 8–02

153 In American specifications for cold-formed stainless steel (SEI/ASCE 8–02 [17]), two separate
154 equations have been provided for the bending-shear interaction, which are for sections with
155 and without transverse stiffeners. From Eq. (7), SEI/ASCE 8–02 [17] provision for sections
156 with transverse stiffeners is given and this takes into account the bending-shear interaction
157 when the applied bending moment (M) exceeds half of the section nominal moment capacity
158 (M_n) and when the applied shear force (V) is greater than 70 % of the section nominal shear
159 capacity (V_n).

$$160 \quad 0.6 \left(\frac{M}{M_n} \right) + \left(\frac{V}{V_n} \right) \leq 1.3 \text{ for } \frac{M}{M_n} > 0.5 \text{ and } \frac{V}{V_n} > 0.7 \quad (7)$$

161 For the calculation of nominal capacities, the direct strength method (DSM) can be
162 incorporated. The nominal bending strength for local buckling (M_{nl}) from AISI S100 [20] can
163 be used to determine the nominal bending strength (M_n) and is expressed in Eqs. (8) and (9).

$$164 \quad M_{nl} = M_{ne} \text{ for } \lambda_1 \leq 0.776 \quad (8)$$

165
$$M_{nl} = \left[1 - 0.15 \left(\frac{M_{cr1}}{M_{ne}} \right)^{0.4} \right] \left(\frac{M_{cr1}}{M_{ne}} \right)^{0.4} M_{ne} \text{ for } \lambda_l > 0.776 \quad (9)$$

166 where M_{ne} is the critical elastic lateral-torsional buckling moment, M_{cr1} is the critical elastic
167 local buckling moment, and λ_l is the section slenderness.

168 The nominal shear strength (V_n) can be calculated from AISI S100 [20] using Eqs. (10) and
169 (11).

170
$$V_n = V_y \text{ for } \lambda_v \leq 0.776 \quad (10)$$

171
$$V_n = \left[1 - 0.15 \left(\frac{V_{cr}}{V_y} \right)^{0.4} \right] \left(\frac{V_{cr}}{V_y} \right)^{0.4} V_y \text{ for } \lambda_v > 0.776 \quad (11)$$

172 where V_y is the shear yield force, V_{cr} is the elastic shear buckling force, and λ_v is the section
173 slenderness.

174 Dissanayake et al. [19] also proposed modified set of equations to determine the shear strength
175 of cold-formed stainless steel lipped channel sections using DSM and these DSM provisions
176 are expressed in Eqs. (12)-(14).

177
$$V_n = 2V_y \text{ for } \lambda_v \leq 0.122 \quad (12)$$

178
$$V_n = \frac{0.795}{\lambda_v^{0.439}} V_y \text{ for } 0.122 < \lambda_v \leq 0.592 \quad (13)$$

179
$$V_n = \left[1 - 0.213 \left(\frac{V_{cr}}{V_y} \right)^{0.35} \right] \left(\frac{V_{cr}}{V_y} \right)^{0.35} V_y \text{ for } \lambda_v > 0.592 \quad (14)$$

180 In addition to this linear interaction equation, a circular interaction equation is also provided in
181 SEI/ASCE 8-02 [17] for sections without transverse stiffeners and this is similar to the
182 expression given in Eq. (2).

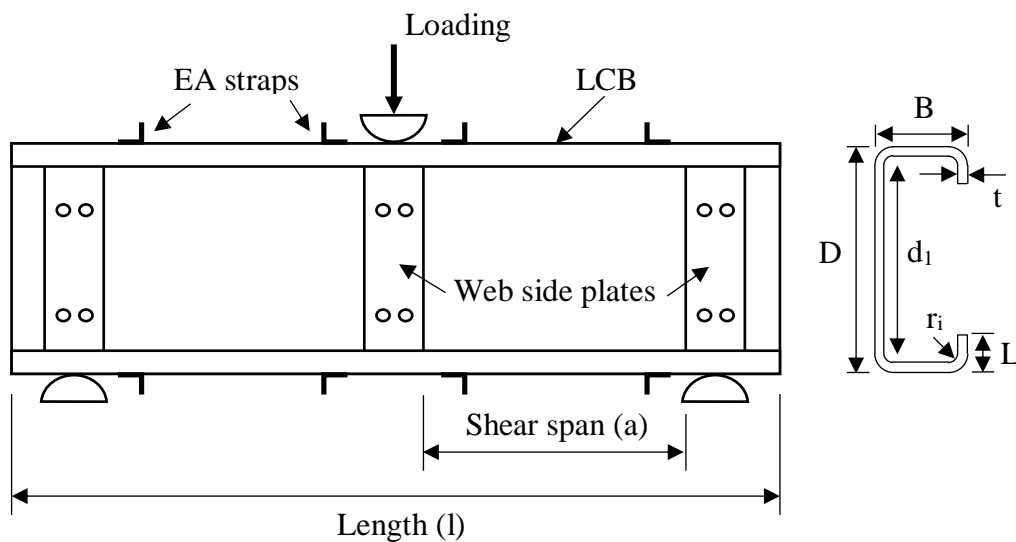
183 **3 Finite element (FE) modelling**

184 Commercially available ABAQUS CAE 2017 software package was employed to develop the
185 FE models to investigate the bending and shear interaction behaviour of cold-formed stainless
186 steel lipped channel sections. The details of numerical simulations carried out are similar to the
187 numerical modelling outlined in Dissanayake et al. [19] and are summarised in this section.

188 3.1 General

189 Three-point loading tests of LCBs found from [7],[19] were simulated in ABAQUS to study
 190 the bending-shear interaction. To avoid any torsional effects on the structural behaviour of
 191 LCBs, back-to-back beam setup has been employed by attaching two LCBs from their webs in
 192 the experiments. Simply supported boundary conditions and mid-span loading have been
 193 assigned to the sections through hot-rolled T-stiffeners. The T-stiffeners have been bolted to
 194 two LCBs using web side plates to avoid any web bearing failure. Both top and bottom flanges
 195 have been restrained against distortional buckling by screwing equal angle (EA) straps to them
 196 at the loading point and at two supports. More details of these three-point loading tests can be
 197 found in [7],[19],[21]–[23]. However, considering the symmetry of the test setup, single LCBs
 198 were simulated with three web side plates in the FE models developed in this study. The
 199 schematic diagram of three-point loading test setup and cross-sectional dimensions of a LCB
 200 section are shown in Fig. 1. In the FE modelling, the shear behaviour and the bending-shear
 201 interaction behaviour of LCBs were simulated using this setup.

202 In addition, it was required to study the bending behaviour of LCBs to find out their bending
 203 capacities. For this purpose, four-point bending test setup given in [8] was utilised and then FE
 204 models were developed for each cross-section considered in this study. More details of four-
 205 point bending tests can be found in [8],[24].

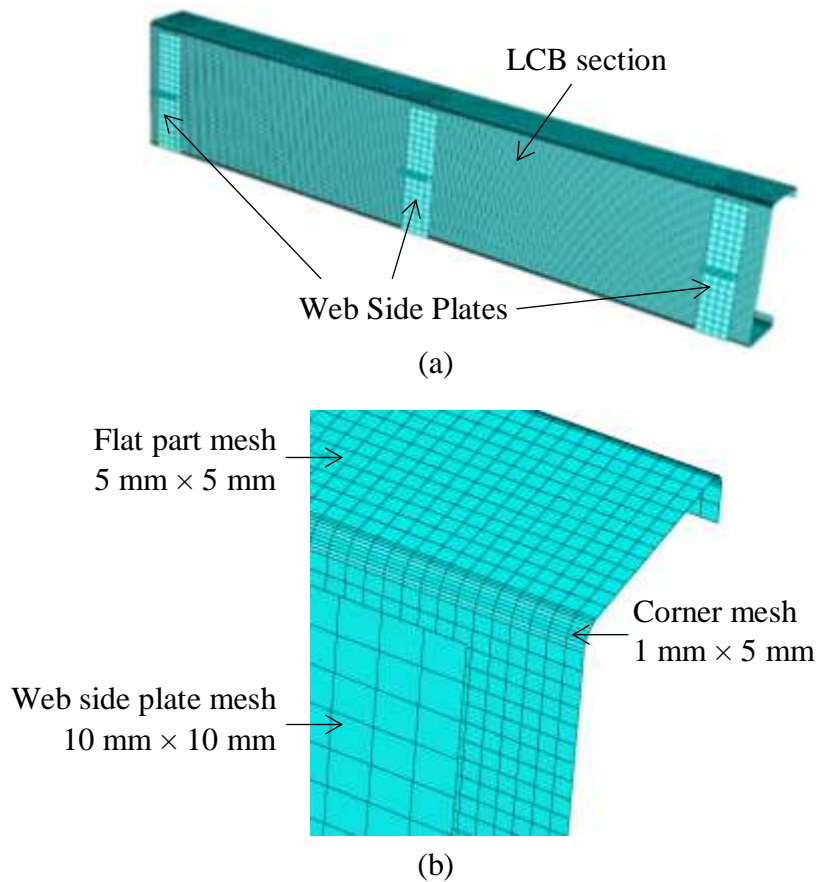


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207 Fig. 1 Schematic diagram of three-point loading arrangement and cross-sectional dimensions

208 3.2 Element type and mesh

209 The four-node shell element type known as S4R was chosen from ABAQUS element library
210 to model both LCB sections and web side plates. These S4R shell elements have six degrees
211 of freedom (DOFs) at each node. Mesh sensitivity analysis suggested that the assigning of 5
212 mm × 5 mm mesh for flat parts of LCB sections and assigning of a relatively finer mesh of 1
213 mm × 5 mm for corner regions of LCB sections are sufficient. However, as web side plates are
214 less important, a comparatively coarser mesh of 10 mm × 10 mm was used for modelling them.
215 Fig. 2 illustrates the assembly of parts together with the FE mesh assigned in the modelling.



216

217 Fig. 2 (a) Assembly of parts and (b) FE mesh used in the modelling

218 3.3 Material modelling of stainless steel

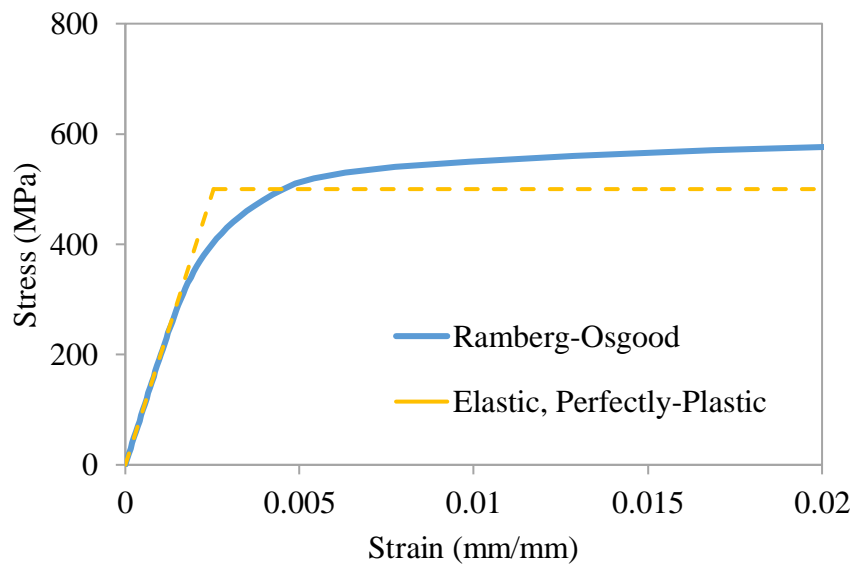
219 Arrayago et al. [25] have recently proposed modifications to the two-stage Ramberg-Osgood
220 material model. The modified two-stage Ramberg-Osgood material model with these recent
221 proposals was incorporated in calculating stress-strain data for stainless steel in this study.
222 Then, true stress (σ_{true}) and log plastic strain ($\epsilon_{\text{ln}}^{\text{pl}}$) data of the non-linear material was inputted

223 into ABAQUS. The true stress (σ_{true}) and log plastic strain ($\epsilon_{\text{ln}}^{\text{pl}}$) were calculated using Eqs.
 224 (15) and (16), respectively. The strength enhancements induced during the press-braking
 225 process of LCB sections were introduced to the corner regions as described in [19]. For the FE
 226 modelling of carbon steel sections, an elastic, perfectly-plastic material model was employed.
 227 The incorporated material models are illustrated in Fig. 3.

$$228 \quad \sigma_{\text{true}} = \sigma_{\text{nom}}(1 + \epsilon_{\text{nom}}) \quad (15)$$

$$229 \quad \epsilon_{\text{ln}}^{\text{pl}} = \ln(1 + \epsilon_{\text{nom}}) - \frac{\sigma_{\text{true}}}{E} \quad (16)$$

230 where σ_{nom} is the engineering stress, ϵ_{nom} is the engineering strain, and E is Young's
 231 modulus.



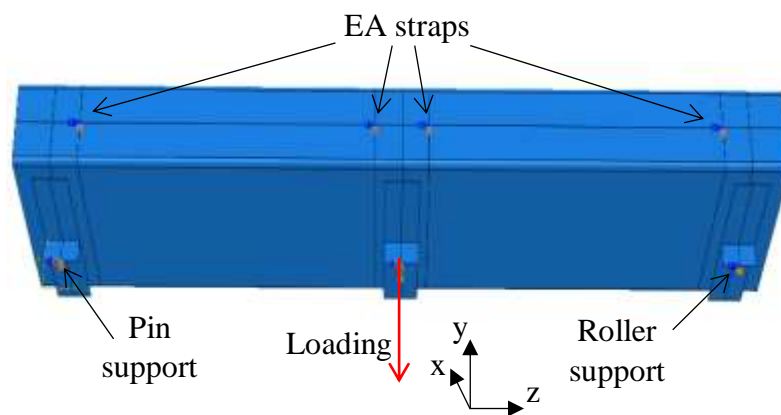
232

233 Fig. 3 Different material models used in the FE modelling

234 During the section forming, two types of residual stresses are formed in press-braked sections
 235 and these are known as bending and membrane residual stresses. The bending residual stresses
 236 are indirectly accounted in material stress-strain data while membrane residual stresses are
 237 found to be negligible for press-braked sections [26]. The similar numerical studies have also
 238 ignored the residual stresses arising from the section forming in the numerical modelling as
 239 these residual stresses have very small effect [26],[27]. Therefore, the effect of these residual
 240 stresses were not explicitly considered in the FE modelling of this study.

241 3.4 Boundary conditions

242 The boundary conditions were chosen as they accurately simulate the experimental conditions.
243 All three translational DOFs were restrained at one end to maintain a pin support condition
244 while only the translational DOFs in the cross-sectional plane were restrained at the other end
245 to maintain a roller support condition. To avoid any rotation of the section, the rotational DOF
246 about the longitudinal axis was restrained at both supports. The loading was given at the mid-
247 span by applying a vertical displacement. The loading and the support conditions were assigned
248 to web side plates to suppress any web bearing failure at these locations. The translational DOF
249 in the transverse direction and the rotational DOF about the longitudinal axis were restrained
250 at the EA strap locations to eliminate distortional buckling. To simulate bolted connections
251 between LCB web and web side plates, tie constraints (available in ABAQUS) were assigned.
252 The locations of the assigned boundary conditions in the FE modelling are given in Fig. 4.



253

254 Fig. 4 The locations of the boundary conditions assigned in the FE modelling

255 3.5 Analysis methods

256 To account for geometric imperfections in the non-linear analysis, first, an Eigenvalue buckling
257 analysis was conducted on the perfect geometry. Then, the critical buckling Eigenmode shapes
258 were extracted from the analysis. The web shear buckling mode with the lowest Eigenvalue
259 was chosen from each analysis. Thereafter, these critical mode shapes were superimposed on
260 to the non-linear FE models using a suitable scale factor which represents the magnitude of
261 imperfections. In this study, the modified Dawson and Walker model proposed by Gardner and
262 Nethercot [28] was used as the imperfection amplitude (ω_0). The modified Dawson and
263 Walker model is given by Eq. (17).

264 $\omega_0 = 0.023 \left(\frac{\sigma_{0.2}}{\sigma_{cr}} \right) t$ (17)

265 where $\sigma_{0.2}$ is the 0.2 % proof stress of the material, σ_{cr} is the critical elastic buckling stress of
266 the most slender element of the section, and t is the thickness.

267 Secondly, a modified static Riks analysis was performed on the geometrically and materially
268 non-linear FE models until the failure occurs, to study the section behaviour. More details
269 related to FE modelling of cold-formed channel sections can be found from [29]–[31].

270 **4 Validation of FE models**

271 Comparisons of the FE results obtained from the developed models were compared with the
272 experimental results found from the literature and those details are given in this section. The
273 shear, bending, and bending-shear interaction tests were covered in this validation process.

274 In this paper, LCB cross-sections are denoted as LCB $D \times B \times L \times t$. This notation stands for
275 key cross-sectional dimensions in millimetres where D is the section depth, B is the flange
276 width, L is the lip height, and t is the section thickness. These cross-sectional dimensions are
277 defined in Fig. 1.

278 4.1 Shear behaviour

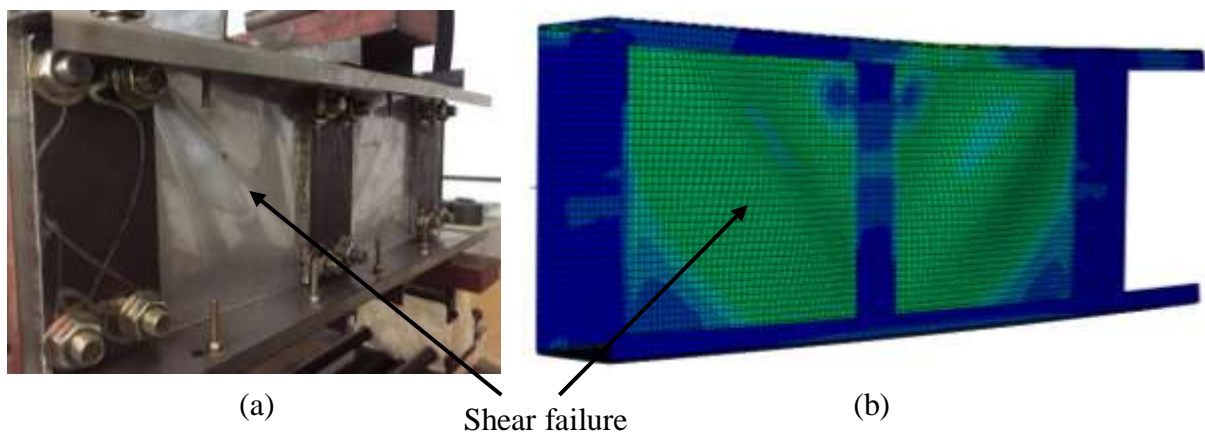
279 Dissanayake et al. [19] have investigated the shear behaviour of cold-formed stainless steel
280 LCBs using three-point loading tests. These experimental results are compared with the FE
281 results in Table 3 for the validation of FE modelling for shear behaviour. The section length
282 and the shear span length for each section are also given in Table 3. The shear span (a) to clear
283 web depth (d_1) ratio is taken as the aspect ratio of the specimen and the definition of these
284 parameters are illustrated in Fig.1. The shear capacity of a section is independent of its bending
285 stresses when shorter spans (such as sections with an aspect ratio of 1.0) are employed while
286 the bending-shear interaction is taken place when longer spans are employed [7]. Therefore,
287 all the compared sections have an aspect ratio of 1.0. From the comparisons, it can be seen that
288 the mean and the coefficient of variation (COV) of experimental to FE shear capacity ratio are
289 1.02 and 0.073, respectively. This confirms the ability of developed FE models to predict the
290 shear capacities of cold-formed stainless steel LCBs with good accuracy. Additionally, Fig. 5
291 compares the experimental and FE shear failure modes for LCB $200 \times 75 \times 15 \times 1.2$ section. It can
292 be concluded from Fig. 5, that the developed FE models are able to accurately capture the

293 diagonal shear failures of LCB webs as well. The experimental and FE load-deflection curves
 294 of LCB 150×65×15×2.0 section are also compared in Fig. 6. The slip between the plates and
 295 specimens at the bolted connections could be the reason for higher deflections in the
 296 experiments compared to FE results.

297 Table 3 Comparison of experimental [19] and FE section capacities for stainless steel LCBs subjected to shear

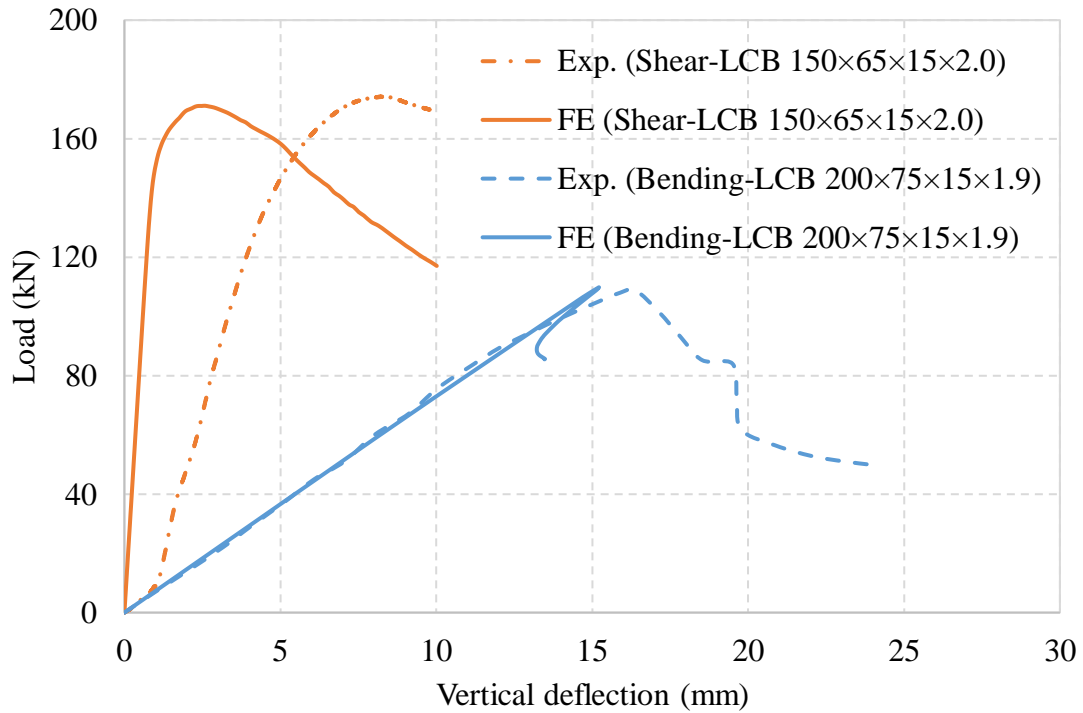
LCB section	l (mm)	a (mm)	$\bar{\lambda}_w$	$V_{Exp.}$ (kN)	V_{FE} (kN)	$\frac{V_{Exp.}}{V_{FE}}$
LCB 100×50×15×1.2	380	97.5	0.78	18.49	16.86	1.10
LCB 100×50×15×1.5	379	97.0	0.61	24.44	23.90	1.02
LCB 100×50×15×2.0	376	95.5	0.45	36.00	32.72	1.10
LCB 150×65×15×1.2	479	147.0	1.17	21.60	20.09	1.08
LCB 150×65×15×1.5	479	147.0	0.92	26.26	28.40	0.92
LCB 150×65×15×2.0	478	146.5	0.69	43.55	42.60	1.02
LCB 200×75×15×1.2	579	197.0	1.57	22.98	22.97	1.00
LCB 200×75×15×2.0	579	197.0	0.93	47.05	52.11	0.90
Mean						1.02
COV						0.073

298



299

300 Fig. 5 (a) Experimental [19] and (b) FE failure modes of stainless steel LCB 200×75×15×1.2 section subjected to
 301 shear



302

303 Fig. 6 Comparison of experimental and FE load-deflection curves

304 4.2 Bending behaviour

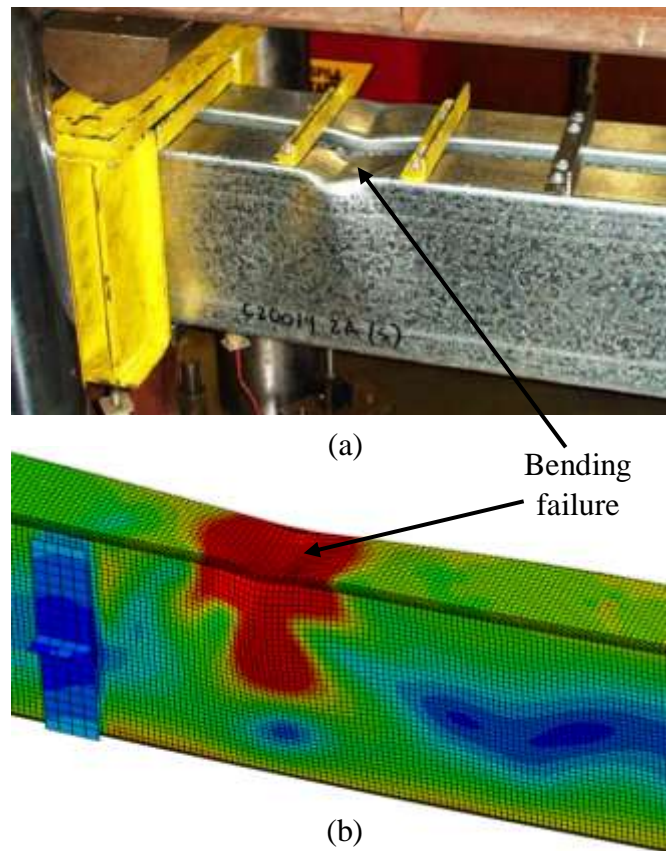
305 To study the bending behaviour, four-point bending tests of cold-formed steel LCB sections
 306 found from Pham and Hancock [8] were simulated in ABAQUS. A specimen length of 2695
 307 mm was utilised in the FE modelling according to bending tests conducted by Pham and
 308 Hancock [8]. In the FE modelling, an elastic, perfectly-plastic material model was employed
 309 for cold-formed steel, with no consideration given to corner strength enhancements.
 310 Experimental and FE ultimate loads of four-point bending tests of cold-formed steel LCB
 311 sections are compared in Table 4. In Table 4, P is the ultimate load. The experimental to FE
 312 ultimate load ratio has a mean and a COV of 1.02 and 0.056, respectively. Therefore, good
 313 accuracy of capacity predictions is evident from the comparisons. In addition, comparisons are
 314 made between experimental and FE failure modes in Fig. 7 and experimental and FE load-
 315 deflection curves in Fig. 6 for LCB 200x75x15x1.9 section. Both these comparisons show
 316 good agreement as well. Therefore, the elaborated FE models can be utilised to study the
 317 bending response of cold-formed stainless steel LCB sections.

318

319 Table 4 Comparison of experimental [8] and FE section capacities for cold-formed steel LCBs subjected to
 320 bending

LCB section	$P_{Exp.}$ (kN)	$M_{Exp.}$ (kNm)	P_{FE} (kN)	M_{FE} (kNm)	$\frac{P_{Exp.}}{P_{FE}}$
LCB 150×65×15×1.5	52.13	10.43	53.64	10.73	0.97
LCB 150×65×15×2.4	99.19	19.84	90.04	18.01	1.10
LCB 200×75×15×1.5	67.33	13.47	66.00	13.20	1.02
LCB 200×75×15×1.9	108.78	21.76	109.80	21.96	0.99
Mean					1.02
COV					0.056

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322

323 Fig. 7 (a) Experimental [8] and (b) FE failure modes of cold-formed steel LCB 200×75×15×1.9 section
 324 subjected to bending

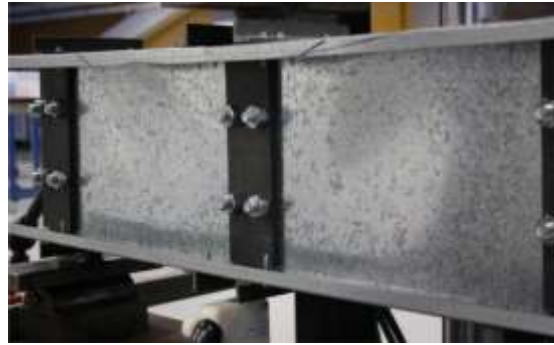
325 4.3 Bending-shear interaction behaviour

326 Keerthan and Mahendran [7] have investigated the bending-shear interaction behaviour of
 327 cold-formed steel LCB sections with an aspect ratio (a/d_1) of 1.5 using three-point loading tests.
 328 These tests were simulated in the FE modelling and results were compared. Table 5 summarises
 329 the experimental and FE capacities. From the comparisons, it can be seen that the experimental
 330 to FE shear capacity ratio has a mean of 1.01 and a COV of 0.067. Therefore, the capacity
 331 prediction accuracy of the FE models is highlighted for higher aspect ratios as well. Moreover,
 332 good agreement can be seen between experimental and FE bending-shear interaction failure
 333 modes for LCB 250×75×18×1.9 section in Fig. 8.

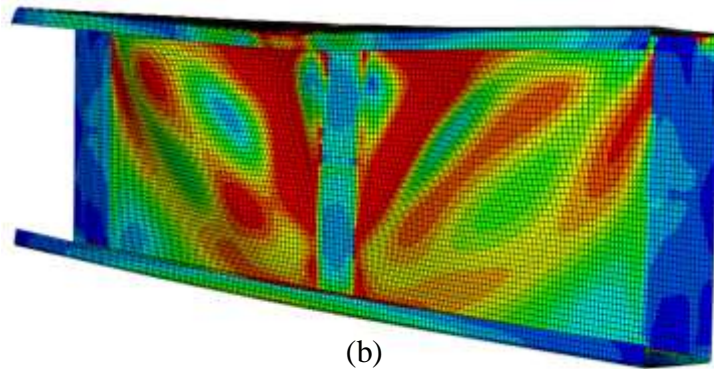
334 Table 5 Comparison of experimental [7] and FE section capacities for cold-formed steel LCBs subjected to
 335 bending-shear interaction

LCB section	l (mm)	a (mm)	$\bar{\lambda}_w$	$V_{Exp.}$ (kN)	$M_{Exp.}$ (kNm)	V_{FE} (kN)	M_{FE} (kNm)	$\frac{V_{Exp.}}{V_{FE}}$ or $\frac{M_{Exp.}}{M_{FE}}$
LCB 160×65×15×1.5	654	156.4	1.61	39.70	9.31	38.77	9.10	1.02
LCB 160×65×15×1.9	659	158.0	1.26	56.80	13.46	53.50	12.68	1.06
LCB 200×75×15×1.5	775	196.8	2.05	38.10	11.25	41.30	12.19	0.92
LCB 200×75×15×1.9	776	197.0	1.58	56.91	16.82	58.77	17.37	0.97
LCB 200×75×15×1.95	776	197.0	1.12	39.51	11.68	36.38	10.75	1.09
LCB 250×75×18×1.5	927	247.2	2.56	42.90	15.91	44.50	16.50	0.96
LCB 250×75×18×1.9	927	247.3	1.98	60.70	22.52	64.28	23.84	0.94
LCB 250×75×18×1.95	929	248.0	1.41	44.37	16.51	40.55	15.08	1.09
Mean								1.01
COV								0.067

336



(a)



(b)

337

338 Fig. 8 (a) Experimental [7] and (b) FE failure modes of cold-formed steel LCB 250×75×18×1.9 section subjected
339 to bending-shear interaction

340 5 Numerical parametric study

341 5.1 General

342 A comprehensive parametric study was conducted to generate a numerical database covering
343 a wider area of different parameters following the successful validation of developed FE
344 models. Then, this numerical data was utilised to investigate the bending and shear interaction
345 behaviour of cold-formed stainless steel LCBs.

346 Three scenarios were considered in the study. The validated FE models of three-point loading
347 tests with shorter spans (in Section 4.1) were utilised to simulate the shear behaviour while the
348 validated FE models of three-point loading tests with longer spans (in Section 4.3) were
349 considered to simulate the bending-shear interaction behaviour. In addition, the validated FE
350 models of four-point bending tests (in Section 4.2) were incorporated to simulate the bending
351 behaviour and to find out the bending capacities of varying LCB sections considered in the
352 parametric study. Altogether 12 different cross sections were considered with two section
353 depths (D), three section thicknesses (t) and two stainless steel grades. To vary the level of

354 bending-shear interaction, a total of 48 FE models were developed with four different aspect
 355 ratio (a/d_1) values. Table 6 summarises these parameters used in the study.

356 Table 6 Summary of the parameters considered in the study

Scenario	Sections	a/d_1	l (mm)	t (mm)	Stainless steel grade	No. of models
1. Four-point bending simulation	LCB 150×65×15×t	-	2695	1	Austenitic-1.4301	12
	LCB 200×75×20×t			1.5 2	Duplex-1.4462	
2. Three-point loading simulation with shorter spans	LCB 150×65×15×t	1	485	1	Austenitic-1.4301	12
	LCB 200×75×20×t	1	585	1.5 2	Duplex-1.4462	
3. Three-point loading simulation with longer spans	LCB 150×65×15×t	1.5	635	1	Austenitic-1.4301	48
		2	785	1.5	Duplex-1.4462	
		3	1085	2		
		5	1685			
	LCB 200×75×20×t	1.5	785			
		2	985			
		3	1385			
		5	2185			

357

358 Both austenitic and duplex stainless steel grades were considered in the study and Table 7 brief
 359 the basic material properties employed in the FE models where f_y is the yield stress, f_u is the
 360 ultimate stress, ϵ_u is the ultimate strain, and n and m are Ramberg-Osgood parameters. The
 361 yield stress (f_y) and the ultimate stress (f_u) values for each stainless steel grade were taken from
 362 EN1993-1-4 [11] and the recommendations of Arrayago et al. [25] were adopted for the
 363 ultimate strain (ϵ_u) and Ramberg-Osgood parameters. Young's modulus was taken as 200,000
 364 MPa and a value of 0.3 was used for Poisson's ratio. The stress-strain relationships of two
 365 stainless steel grades considered are illustrated in Fig. 9.

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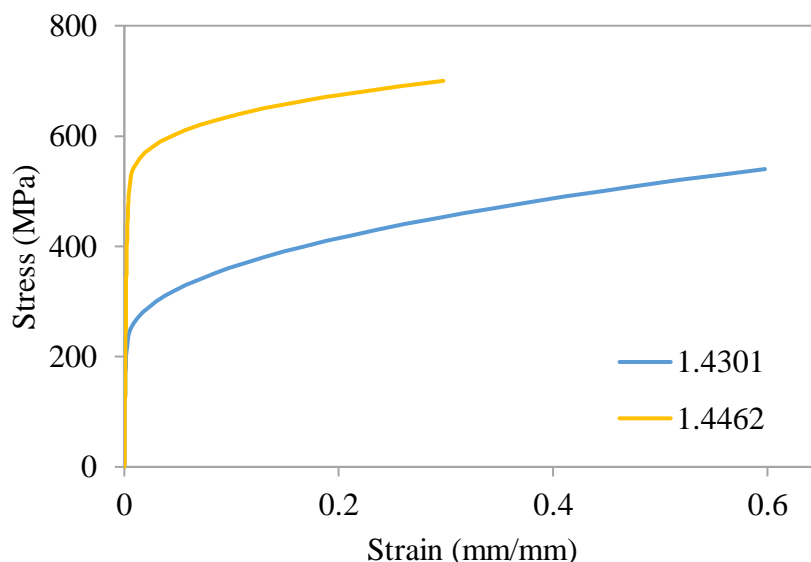
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369 Table 7 Material properties used in the parametric study

Stainless steel grade	f_y (MPa)	f_u (MPa)	ϵ_u	n	m
Austenitic-1.4301	230	540	0.57	7	2.19
Duplex-1.4462	500	700	0.29	8	3.00

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372 Fig. 9 Stress-strain curves for 1.4301 and 1.4462 stainless steel grades

373 5.2 Comparison of FE results with Eurocode 3 and the DSM predictions

374 The numerical parametric study results are summarised in this section. Table 8 compares the
 375 cross-sectional bending capacities ($M_{u,FE}$) found from the FE simulations of four-point bending
 376 setup (Scenario 1 in Table 6) with the Eurocode 3 predictions of moment resistance (M_{EC3}) and
 377 the DSM predictions of moment capacity (M_{DSM}). In Table 8, M_{EC3} was calculated from Eq.
 378 (5) while M_{DSM} was evaluated from Eqs. (8) and (9). From the mean and the COV of FE to
 379 predicted capacity ratio, it can be concluded that the code predictions are too conservative for
 380 cold-formed stainless steel LCBs. Therefore, the numerical values of cross-section bending
 381 resistance ($M_{u,FE}$) were adopted in the evaluation of bending-shear interaction equations in
 382 Section 6.

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386 Table 8 Numerical parametric study results of Scenario 1

LCB section	$M_{u,FE}$ (kNm)	M_{EC3} (kNm)	M_{DSM} (kNm)	$\frac{M_{u,FE}}{M_{EC3}}$	$\frac{M_{u,FE}}{M_{DSM}}$
Stainless steel grade					
1.4301					
LCB 150×65×15×1.0	3.06	2.34	2.73	1.30	1.12
LCB 150×65×15×1.5	5.75	4.55	4.95	1.26	1.16
LCB 150×65×15×2.0	8.05	6.43	6.48	1.25	1.24
LCB 200×75×20×1.0	4.30	3.33	3.85	1.29	1.11
LCB 200×75×20×1.5	8.72	6.60	7.50	1.32	1.16
LCB 200×75×20×2.0	12.80	10.41	10.72	1.23	1.19
Stainless steel grade					
1.4462					
LCB 150×65×15×1.0	4.98	3.81	4.54	1.31	1.10
LCB 150×65×15×1.5	10.06	7.64	8.86	1.32	1.14
LCB 150×65×15×2.0	15.24	12.20	13.99	1.25	1.09
LCB 200×75×20×1.0	6.85	5.34	6.36	1.28	1.08
LCB 200×75×20×1.5	13.78	10.92	12.58	1.26	1.10
LCB 200×75×20×2.0	23.26	17.75	20.12	1.31	1.16
Mean				1.28	1.14
COV				0.024	0.043

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388 The parametric study results of FE simulations of three-point loading setup for $a/d_1=1.0$
389 (Scenario 2 in Table 6) are summarised in Table 9 while Tables 10-13 provide that of the
390 sections with longer spans (Scenario 3 in Table 6). In Tables 9-13, V and M are the numerical
391 values of the shear force and the bending moment at the failure of the section, respectively.
392 $V_{EC3,[19]}$ is the shear resistance of the section according to Eurocode 3 for stainless steel
393 calculated from Eq. (6) where modified expressions for shear buckling reduction factor from
394 [19] (using Table 2) were incorporated. $V_{DSM,[19]}$ is the DSM shear capacity of the section
395 calculated from Eqs. (12)-(14).

396 The mean and the COV of FE to predicted shear capacity ratio given in Table 9 suggest that
397 the numerical shear capacities are agree well with the shear capacity predictions. Therefore,

398 this confirms that the shear capacity of the section is not affected by the bending moment when
399 shorter spans ($a/d_1=1.0$) are employed. In addition, the bending moment of the section (M) is
400 compared with the bending resistance consisting of the effective flange area ($M_{f,Rd}$) in Table 9.
401 This comparison suggests that even though the section moment (M) is as high as $1.3 \times M_{f,Rd}$, the
402 shear capacity (V) of the section is not reduced.

403 Further, the progressive reduction of the section shear force (V) compared to the section shear
404 resistance is observed with the increment of the section bending moment (M) compared to the
405 section bending resistance from Tables 10-13. This confirms that the numerically obtained
406 shear capacities of the sections with longer spans are not independent of bending stresses of
407 the section. Therefore, the shear provisions given in Section 2 were utilised to calculate the
408 shear resistances of sections when evaluating the bending-shear interaction equations in
409 Section 6. However, no reduction in section bending moment (M) can be observed for sections
410 with aspect ratios of 3.0 and 5.0 from Tables 12 and 13.

411 Moreover, FE results shows that the employed duplex stainless steel grade results in higher
412 shear forces and bending moments in the sections than austenitic stainless steel grade.
413 However, no clear difference was observed in the interaction behaviour of the sections of these
414 two stainless steel grades from the numerical results of the parametric study.

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425 Table 9 Numerical parametric study results of Scenario 2 ($a/d_1=1.0$)

LCB section	V (kN)	M (kNm)	$V_{EC3,[19]}$ (kN)	$V_{DSM,[19]}$ (kN)	$\frac{V}{V_{EC3,[19]}}$	$\frac{V}{V_{DSM,[19]}}$	$\frac{M}{M_{u,FE}}$	$\frac{M}{M_{f,Rd}}$
Stainless steel grade								
1.4301								
LCB 150×65×15×1.0	15.25	2.27	14.27	13.89	1.07	1.10	0.74	1.28
LCB 150×65×15×1.5	27.62	4.10	25.91	25.55	1.07	1.08	0.71	1.18
LCB 150×65×15×2.0	40.15	5.94	38.66	38.53	1.04	1.04	0.74	1.19
LCB 200×75×20×1.0	17.23	3.43	16.24	15.82	1.06	1.09	0.80	1.38
LCB 200×75×20×1.5	32.19	6.39	30.42	29.65	1.06	1.09	0.73	1.27
LCB 200×75×20×2.0	48.90	9.68	46.25	45.59	1.06	1.07	0.76	1.21
Stainless steel grade								
1.4462								
LCB 150×65×15×1.0	25.69	3.83	24.79	24.22	1.04	1.06	0.77	1.37
LCB 150×65×15×1.5	50.58	7.51	46.82	45.56	1.08	1.11	0.75	1.30
LCB 150×65×15×2.0	76.38	11.30	71.57	70.28	1.07	1.09	0.74	1.21
LCB 200×75×20×1.0	28.21	5.61	27.44	27.29	1.03	1.03	0.82	1.47
LCB 200×75×20×1.5	57.15	11.34	53.40	51.99	1.07	1.10	0.82	1.39
LCB 200×75×20×2.0	88.82	17.59	83.51	81.25	1.06	1.09	0.76	1.30
Mean					1.06	1.08	0.76	1.30
COV					0.015	0.022	0.046	0.070

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434 Table 10 Numerical parametric study results of Scenario 3 ($a/d_1=1.5$)

LCB section	V (kN)	M (kNm)	$V_{EC3,[19]}$ (kN)	$V_{DSM,[19]}$ (kN)	$\frac{V}{V_{EC3,[19]}}$	$\frac{V}{V_{DSM,[19]}}$	$\frac{M}{M_{u,FE}}$
Stainless steel grade							
1.4301							
LCB 150×65×15×1.0	12.07	2.70	13.25	13.32	0.91	0.91	0.88
LCB 150×65×15×1.5	22.49	5.01	24.39	24.63	0.92	0.91	0.87
LCB 150×65×15×2.0	33.01	7.33	36.61	37.34	0.90	0.88	0.91
LCB 200×75×20×1.0	13.34	3.98	14.93	15.14	0.89	0.88	0.93
LCB 200×75×20×1.5	26.19	7.80	28.34	28.48	0.92	0.92	0.89
LCB 200×75×20×2.0	39.69	11.79	43.52	43.94	0.91	0.90	0.92
Stainless steel grade							
1.4462							
LCB 150×65×15×1.0	19.18	4.29	22.73	23.16	0.84	0.83	0.86
LCB 150×65×15×1.5	39.76	8.86	43.50	43.71	0.91	0.91	0.88
LCB 150×65×15×2.0	62.30	13.83	67.16	67.66	0.93	0.92	0.91
LCB 200×75×20×1.0	20.89	6.24	24.93	26.05	0.84	0.80	0.91
LCB 200×75×20×1.5	43.73	13.02	49.12	49.75	0.89	0.88	0.94
LCB 200×75×20×2.0	71.84	21.34	77.57	77.95	0.93	0.92	0.92
Mean					0.90	0.89	0.90
COV					0.034	0.043	0.027

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443 Table 11 Numerical parametric study results of Scenario 3 ($a/d_1=2.0$)

LCB section	V (kN)	M (kNm)	$V_{EC3,[19]}$ (kN)	$V_{DSM,[19]}$ (kN)	$\frac{V}{V_{EC3,[19]}}$	$\frac{V}{V_{DSM,[19]}}$	$\frac{M}{M_{u,FE}}$
Stainless steel grade							
1.4301							
LCB 150×65×15×1.0	9.76	2.91	12.82	13.02	0.76	0.75	0.95
LCB 150×65×15×1.5	18.20	5.41	23.74	24.13	0.77	0.75	0.94
LCB 150×65×15×2.0	26.29	7.78	35.78	36.68	0.73	0.72	0.97
LCB 200×75×20×1.0	10.63	4.23	14.38	14.77	0.74	0.72	0.98
LCB 200×75×20×1.5	21.18	8.41	27.47	27.85	0.77	0.76	0.96
LCB 200×75×20×2.0	31.95	12.65	42.35	43.06	0.75	0.74	0.99
Stainless steel grade							
1.4462							
LCB 150×65×15×1.0	15.26	4.55	21.87	22.60	0.70	0.68	0.91
LCB 150×65×15×1.5	32.27	9.58	42.10	42.72	0.77	0.76	0.95
LCB 150×65×15×2.0	50.04	14.81	65.28	66.25	0.77	0.76	0.97
LCB 200×75×20×1.0	16.32	6.50	23.91	25.39	0.68	0.64	0.95
LCB 200×75×20×1.5	34.73	13.79	47.34	48.56	0.73	0.72	1.00
LCB 200×75×20×2.0	58.15	23.03	75.06	76.19	0.77	0.76	0.99
Mean					0.75	0.73	0.96
COV					0.040	0.52	0.026

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452 Table 12 Numerical parametric study results of Scenario 3 ($a/d_1=3.0$)

LCB section	V (kN)	M (kNm)	$V_{EC3,[19]}$ (kN)	$V_{DSM,[19]}$ (kN)	$\frac{V}{V_{EC3,[19]}}$	$\frac{V}{V_{DSM,[19]}}$	$\frac{M}{M_{u,FE}}$
Stainless steel grade							
1.4301							
LCB 150×65×15×1.0	6.73	3.01	12.48	12.71	0.54	0.53	0.98
LCB 150×65×15×1.5	13.04	5.81	23.22	23.62	0.56	0.55	1.01
LCB 150×65×15×2.0	18.42	8.18	35.11	36.00	0.52	0.51	1.02
LCB 200×75×20×1.0	7.11	4.24	13.96	14.41	0.51	0.49	0.99
LCB 200×75×20×1.5	14.93	8.89	26.78	27.20	0.56	0.55	1.02
LCB 200×75×20×2.0	22.21	13.19	41.43	42.14	0.54	0.53	1.03
Stainless steel grade							
1.4462							
LCB 150×65×15×1.0	10.18	4.55	21.20	22.03	0.48	0.46	0.91
LCB 150×65×15×1.5	22.01	9.81	41.00	41.72	0.54	0.53	0.97
LCB 150×65×15×2.0	35.39	15.71	63.78	64.80	0.55	0.55	1.03
LCB 200×75×20×1.0	10.81	6.45	23.12	24.73	0.47	0.44	0.94
LCB 200×75×20×1.5	23.33	13.89	45.95	47.36	0.51	0.49	1.01
LCB 200×75×20×2.0	40.17	23.86	73.10	74.39	0.55	0.54	1.03
Mean					0.53	0.51	1.00
COV					0.058	0.070	0.037

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461 Table 13 Numerical parametric study results of Scenario 3 ($a/d_1=5.0$)

LCB section	V (kN)	M (kNm)	$V_{EC3,[19]}$ (kN)	$V_{DSM,[19]}$ (kN)	$\frac{V}{V_{EC3,[19]}}$	$\frac{V}{V_{DSM,[19]}}$	$\frac{M}{M_{u,FE}}$
Stainless steel grade							
1.4301							
LCB 150×65×15×1.0	4.23	3.15	12.30	12.46	0.34	0.34	1.03
LCB 150×65×15×1.5	7.97	5.92	22.93	23.21	0.35	0.34	1.03
LCB 150×65×15×2.0	11.24	8.32	34.74	35.45	0.32	0.32	1.03
LCB 200×75×20×1.0	4.31	4.29	13.73	14.11	0.31	0.31	1.00
LCB 200×75×20×1.5	8.99	8.92	26.40	26.69	0.34	0.34	1.02
LCB 200×75×20×2.0	13.46	13.33	40.92	41.41	0.33	0.33	1.04
Stainless steel grade							
1.4462							
LCB 150×65×15×1.0	6.16	4.59	20.84	21.57	0.30	0.29	0.92
LCB 150×65×15×1.5	13.65	10.14	40.40	40.91	0.34	0.33	1.01
LCB 150×65×15×2.0	21.68	16.04	62.96	63.64	0.34	0.34	1.05
LCB 200×75×20×1.0	6.64	6.61	22.69	24.20	0.29	0.27	0.96
LCB 200×75×20×1.5	13.87	13.77	45.20	46.40	0.31	0.30	1.00
LCB 200×75×20×2.0	24.20	23.96	72.02	72.96	0.34	0.33	1.03
Mean					0.33	0.32	1.01
COV					0.060	0.073	0.036

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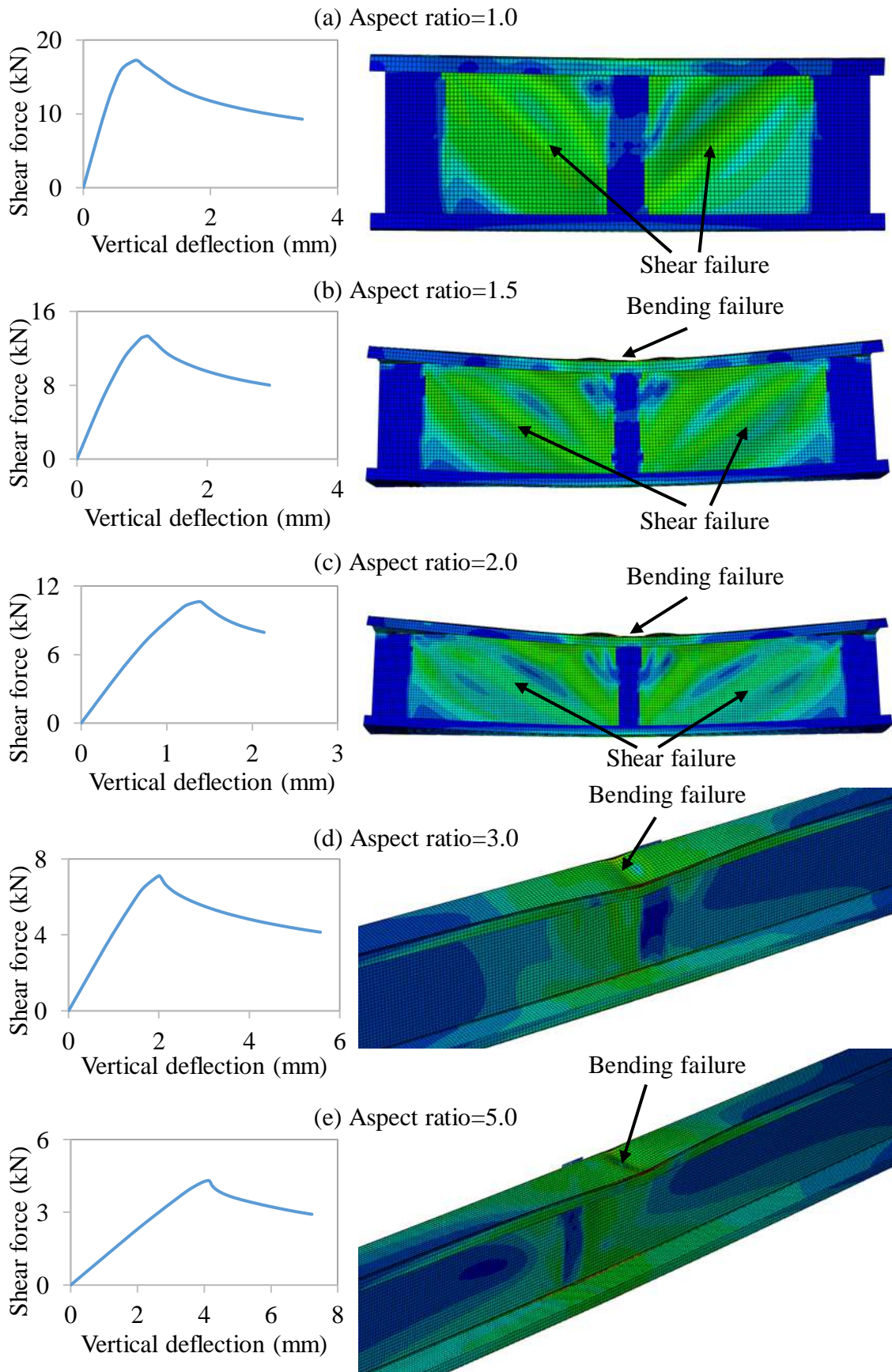
463 **6 Results analysis**

464 The insight into the bending and shear interaction of cold-formed stainless steel LCBs acquired
 465 from the numerical studies conducted in this paper was utilised in assessing the interaction
 466 equations discussed in Section 2 and the details are presented in this section.

467 **6.1 Failure modes**

468 Using the FE results obtained in the parametric study, an analysis of failure modes was
 469 conducted and the dominant failure modes of three-point loading simulations of stainless steel
 470 LCB sections for each aspect ratio were identified. Fig. 10 illustrates the identified dominant
 471 failure modes of stainless steel LCB sections together with their load-deflection curves for each

472 aspect ratio. From Fig. 10 (a), it can be clearly seen that the diagonal shear failure of both webs
473 of sections with an aspect ratio of 1.0, and can be concluded that these sections fail primarily
474 in shear, as it is expected. Figs. 10 (b) and (c) depict the dominant failure modes of sections
475 with aspect ratios of 1.5 and 2.0, respectively. It is observed that both local buckling failure of
476 the compression flange and diagonal shear failure of the webs occur in the sections with these
477 two aspect ratios. Therefore, the sections with aspect ratios of 1.5 and 2.0 are subjected to the
478 bending and shear interaction. Local buckling of the compression flange is visible from Figs.
479 10 (d) and (e) for the sections with aspect ratios of 3.0 and 5.0, respectively, and there is no
480 clear sign of any web shear failure. This observation leads to the conclusion that sections with
481 aspect ratios of 3.0 and 5.0 behave primarily in bending. In the next section, the bending-shear
482 interaction equations discussed in Section 2 were assessed, while giving due consideration to
483 the above findings from FE analysis conducted in this study.

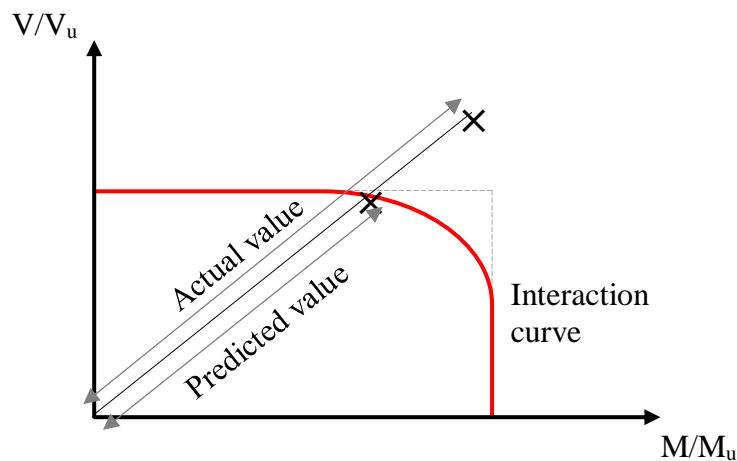


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485 Fig. 10 Failure modes and load-deflection curves of stainless steel LCB sections for different aspect ratios

486 6.2 Assessment of EN1993-1-3 interaction equation

487 The following sections are dealing with the evaluation of codified interaction equations for the
488 bending and shear interaction of cold-formed stainless steel LCB sections using the generated
489 numerical results of the parametric study. For this purpose, numerical resistance values were
490 compared with predicted resistance values. Fig. 11 illustrates the definition of the actual value
491 of the resistance (experimental or FE) with the predicted value of the resistance from an
492 interaction curve. The distance from the origin to the actual data point in the bending-shear
493 interaction diagram defines the actual resistance. The distance between the origin and the
494 intersection point of the origin to the actual data point line and the interaction curve represents
495 the predicted resistance. If the actual data point lies outside the interaction curve, it is said to
496 be a safe prediction and if the point lies within the curve it is said to be unsafe.

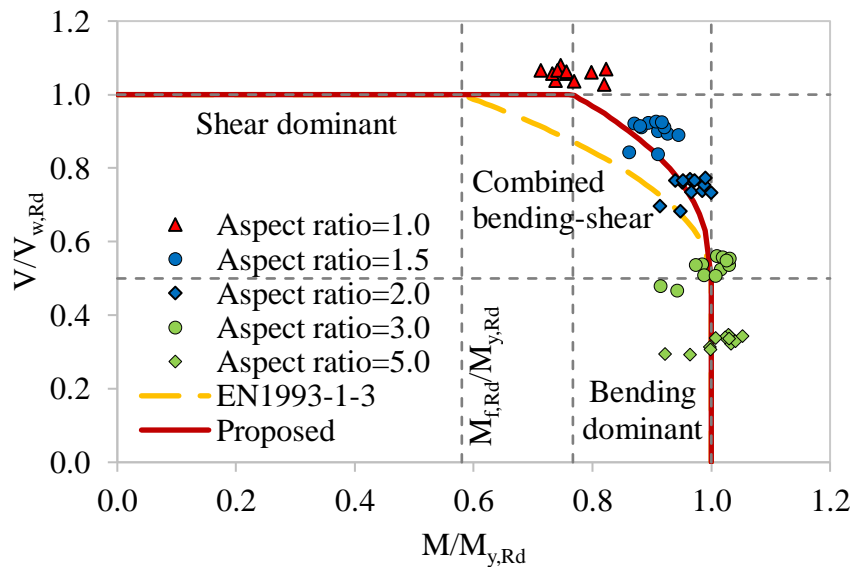


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498 Fig. 11 Definition of actual and predicted resistances with respect to the interaction curve

499 Fig. 12 plots the FE results of stainless steel LCB sections given in Tables 9-13 for each aspect
500 ratio with the bending-shear interaction curve from EN1993-1-3 [12]. It can be observed from
501 the distribution of FE data points in the interaction diagram that LCB sections with an aspect
502 ratio of 1.0 do not exhibit any shear capacity reduction. However, a reduction of shear capacity
503 can be seen for the sections with aspect ratios of 1.5 and 2.0, when the bending and shear
504 interaction effect takes place. Also, there is no evidence of bending capacity reduction in the
505 sections with higher aspect ratios such as 3.0 and 5.0. From the comparison, it can be seen that
506 EN1993-1-3 [12] interaction equation is able to safely predict the resistance of cold-formed
507 stainless steel LCB sections subjected to bending and shear interaction, however, a
508 conservative nature in predictions may exist when $V/V_{w,Rd}$ ratio is closer to 1.0. This is because,
509 the assumption of bending-shear interaction when the applied bending moment (M) exceeds

510 the bending resistance of the flanges with effective flange area ($M_{f,Rd}$), seems to be not
 511 applicable for cold-formed stainless steel LCB sections. It was shown that the shear capacity
 512 of sections with shorter spans is not reduced even with a bending moment higher than $M_{f,Rd}$.
 513 Therefore, modifications were applied to EN1993-1-3 [12] bending-shear interaction equation
 514 with aiming to improve the predictions for cold-formed stainless steel LCBs, employing the
 515 FE results. It can be also observed that there are two specimens with relatively different
 516 behaviour in each set of data corresponding to longer spans, and these specimens are found to
 517 be 1 mm thick sections of duplex stainless steel grade 1.4462. This makes these sections the
 518 most slender specimens among the considered sections as they have the lowest thickness value
 519 of 1 mm and the highest yield stress value of 500 MPa among the considered parameters.
 520 Therefore, the influence of local buckling effects could be the reason for relatively lower
 521 resistances in these slender sections.



522
 523 Fig. 12 FE results of stainless steel LCB sections with different aspect ratios against the current and proposed
 524 EN1993-1-3 [12] interaction curves

525 Following the distribution of FE data points and taking into account the effect of bending-shear
 526 interaction of LCB sections with aspect ratios of 1.5 and 2.0, EN1993-1-3 [12] interaction
 527 equation was modified to the version shown in Eq. (18). When compared to the codified
 528 version, the plastic bending resistance of the section ($M_{pl,Rd}$) is replaced with the bending
 529 resistance of the section ($M_{y,Rd}$) in this proposed interaction equation and the exponent 2.35 is
 530 employed instead of the exponent 2 to redefine the shape of the curve in the bending-shear
 531 interaction region. An additional coefficient of 1.3 is introduced to the term bending resistance

532 consisting of the effective flange area ($M_{f,Rd}$), considering the higher bending moments
533 observed in LCB sections with shorter spans, to redefine the starting point of the bending-shear
534 interaction region.

$$535 \quad \frac{M_{y,Ed}}{M_{y,Rd}} + \left(1 - \frac{1.3 M_{f,Rd}}{M_{y,Rd}}\right) \left(\frac{2V_{Ed}}{V_{w,Rd}} - 1\right)^{2.35} \leq 1.0 \quad (18)$$

536 The comparison of the numerical results with the proposed interaction curve is also shown in
537 Fig. 12. From Fig. 12, it can be seen that there is no reduction in the shear resistance ($V_{w,Rd}$)
538 up to a point closer to the sections with an aspect ratio of 1.0 in the proposed curve. Then, the
539 new curve takes into account the bending and shear interaction of cold-formed stainless steel
540 LCBs up to the location of the sections with an aspect ratio of 3.0 and follows a region of no
541 reduction in cross-section bending resistance ($M_{y,Rd}$). The proposed curve treats the interaction
542 with a curvature and follows well the numerical data points.

543 Then, a statistical evaluation was conducted for both codified and proposed interaction
544 equations. Tables 14 and 15 present the evaluation results calculated according to Fig. 11 for
545 codified and proposed interaction equations, respectively. The mean and the COV of each case
546 are also given in Tables 14 and 15. Table 14 comprises the sections with aspect ratios of 1.0,
547 1.5, and 2.0 as these are treated under bending-shear interaction in EN1993-1-3 [12] provisions.
548 However, only the values corresponding to aspect ratios of 1.5 and 2.0 are considered in Table
549 15 as only these two aspect ratios fall within the proposed interaction region.

550 Overall, the mean and the COV of numerical to predicted ratio are 1.17 and 0.096, respectively
551 for EN1993-1-3 [12] interaction equation while 1.03 and 0.032, respectively for the proposed
552 interaction equation. The reduced mean and COV of the proposed equation compared to the
553 codified interaction equation imply increased accuracy and consistency of predictions.

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560 Table 14 Evaluation of EN1993-1-3 [12] interaction equation according to Fig. 11

LCB section	Aspect ratio=1.0	Aspect ratio=1.5	Aspect ratio=2.0
Stainless steel grade			
1.4301			
LCB 150×65×15×1.0	1.28	1.16	1.06
LCB 150×65×15×1.5	1.16	1.12	1.04
LCB 150×65×15×2.0	1.12	1.12	1.04
LCB 200×75×20×1.0	1.40	1.22	1.09
LCB 200×75×20×1.5	1.23	1.18	1.08
LCB 200×75×20×2.0	1.20	1.16	1.08
Stainless steel grade			
1.4462			
LCB 150×65×15×1.0	1.34	1.10	0.99
LCB 150×65×15×1.5	1.30	1.16	1.07
LCB 150×65×15×2.0	1.21	1.17	1.08
LCB 200×75×20×1.0	1.44	1.17	1.02
LCB 200×75×20×1.5	1.44	1.23	1.10
LCB 200×75×20×2.0	1.28	1.22	1.12
Mean	1.28	1.17	1.06
COV	0.082	0.036	0.033

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570 Table 15 Evaluation of proposed interaction equation for EN1993-1-3 [12] according to Fig. 11

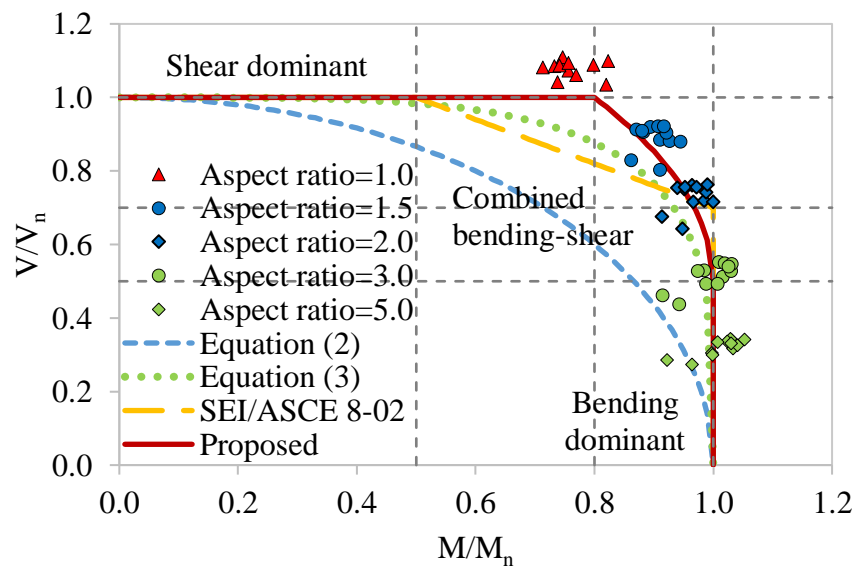
LCB section	Aspect ratio=1.5	Aspect ratio=2.0
Stainless steel grade		
1.4301		
LCB 150×65×15×1.0	1.04	1.01
LCB 150×65×15×1.5	1.01	0.99
LCB 150×65×15×2.0	1.03	1.00
LCB 200×75×20×1.0	1.07	1.03
LCB 200×75×20×1.5	1.06	1.02
LCB 200×75×20×2.0	1.04	1.03
Stainless steel grade		
1.4462		
LCB 150×65×15×1.0	0.97	0.94
LCB 150×65×15×1.5	1.04	1.01
LCB 150×65×15×2.0	1.05	1.02
LCB 200×75×20×1.0	1.02	0.97
LCB 200×75×20×1.5	1.07	1.04
LCB 200×75×20×2.0	1.08	1.05
Mean	1.04	1.01
COV	0.029	0.029

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572 6.3 Assessment of SEI/ASCE 8–02 interaction equation

573 SEI/ASCE 8–02 [17] bending-shear interaction equation for the sections with transverse
574 stiffeners was evaluated for cold-formed stainless steel LCB sections utilising the numerical
575 results generated in the parametric study and the assessment details are given in this section.
576 Fig. 13 compares SEI/ASCE 8–02 [17] interaction curve with the FE results from Tables 9-13.
577 From the comparison, it is apparent that the codified interaction equation is too conservative
578 when the V/V_n ratio is closer to 1.0. This is because SEI/ASCE 8–02 [17] interaction equation
579 treats the LCB sections with an aspect ratio of 1.0 within the bending-shear interaction region
580 as similar to EN1993-1-3 [12] interaction equation. Therefore, SEI/ASCE 8–02 [17] interaction
581 equation was modified considering the distribution of the numerical results.

582 Fig. 13 also includes the circular interaction equation given by Eq. (2) and the rounded
 583 interaction equation given by Eq. (3). It can be concluded from the comparison that the circular
 584 interaction equation is quite conservative for the bending-shear interaction of cold-formed
 585 stainless steel LCB sections. This can be explained by considering the available post-buckling
 586 resistance of the LCB sections, which is not taken into account in the circular interaction
 587 equation. The rounded interaction equation given by Eq. (3) provides optimised predictions for
 588 bending-shear interaction of cold-formed stainless steel LCBs. However, this is also found to
 589 be conservative when the V/V_n ratio is closer to 1.0.



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591 Fig. 13 FE results of stainless steel LCB sections with different aspect ratios against the current and proposed
 592 SEI/ASCE 8-02 [17] interaction curves

593 Considering the bending and shear interaction effect of LCB sections with aspect ratios of 1.5
 594 and 2.0, SEI/ASCE 8-02 [17] interaction equation was modified. The proposed interaction
 595 equation for the bending and shear behaviour of cold-formed stainless steel LCB sections is
 596 given by Eq. (19). This equation adopts a curved interaction as opposed to SEI/ASCE 8-02
 597 [17] interaction equation and takes into account the bending-shear interaction when the applied
 598 bending moment (M) exceeds 80 % of the bending capacity of the section (M_n) and when the
 599 applied shear force (V) is greater than half of the section shear capacity (V_n).

600
$$\left(\frac{M}{M_n}\right) + 0.2 \left(\frac{2V}{V_n} - 1\right)^2 \leq 1.0 \text{ for } \frac{M}{M_n} > 0.8 \text{ and } \frac{V}{V_n} > 0.5 \quad (19)$$

601 Fig. 13 illustrates the comparison of proposed interaction curve with the FE results. It is
602 observed from Fig. 13 that the proposed curve follows well the distribution of the numerical
603 results. Similar to the proposed EN1993-1-3 [12] curve, the proposed SEI/ASCE 8-02 [17]
604 interaction curve also treats the region between the FE data points corresponding to the sections
605 with aspect ratios of 1.0 and 3.0 for the bending-shear interaction of LCB sections.

606 Then, following a similar approach as discussed in Section 6.2, a statistical evaluation was
607 carried out for both codified and proposed SEI/ASCE 8-02 [17] interaction equations as well.
608 The evaluation results are given in Tables 16 and 17 for the codified and proposed interaction
609 equations, respectively with the mean and the COV of each case. Table 16 includes the results
610 of the sections with aspect ratios of 1.0, 1.5, and 2.0 while Table 17 provides the results for the
611 aspect ratios 1.5 and 2.0, as these fall within the bending-shear interaction regions of the
612 codified and proposed interaction curves, respectively.

613 From the evaluation, it was found that the codified interaction equation has an overall mean of
614 1.10 and an overall COV of 0.072 while that for the proposed interaction equation are 1.02 and
615 0.032, respectively. Therefore, relatively lower mean and COV suggest, improved accuracy
616 and consistency of predictions when using the proposed interaction equation.

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627 Table 16 Evaluation of SEI/ASCE 8-02 [17] interaction equation according to Fig. 11

LCB section	Aspect ratio=1.0	Aspect ratio=1.5	Aspect ratio=2.0
Stainless steel grade			
1.4301			
LCB 150×65×15×1.0	1.19	1.10	1.02
LCB 150×65×15×1.5	1.16	1.10	1.01
LCB 150×65×15×2.0	1.14	1.10	1.00
LCB 200×75×20×1.0	1.21	1.11	1.01
LCB 200×75×20×1.5	1.17	1.12	1.03
LCB 200×75×20×2.0	1.17	1.12	1.03
Stainless steel grade			
1.4462			
LCB 150×65×15×1.0	1.17	1.03	0.94
LCB 150×65×15×1.5	1.20	1.11	1.02
LCB 150×65×15×2.0	1.18	1.13	1.03
LCB 200×75×20×1.0	1.17	1.04	0.93
LCB 200×75×20×1.5	1.23	1.11	1.01
LCB 200×75×20×2.0	1.19	1.13	1.04
Mean	1.18	1.10	1.01
COV	0.018	0.029	0.034

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637 Table 17 Evaluation of proposed interaction equation for SEI/ASCE 8-02 [17] according to Fig. 11

LCB section	Aspect ratio=1.5	Aspect ratio=2.0
Stainless steel grade		
1.4301		
LCB 150×65×15×1.0	1.01	1.00
LCB 150×65×15×1.5	1.01	0.99
LCB 150×65×15×2.0	1.03	1.00
LCB 200×75×20×1.0	1.04	1.02
LCB 200×75×20×1.5	1.04	1.02
LCB 200×75×20×2.0	1.05	1.04
Stainless steel grade		
1.4462		
LCB 150×65×15×1.0	0.95	0.94
LCB 150×65×15×1.5	1.01	1.00
LCB 150×65×15×2.0	1.05	1.02
LCB 200×75×20×1.0	0.98	0.96
LCB 200×75×20×1.5	1.06	1.04
LCB 200×75×20×2.0	1.06	1.05
Mean	1.02	1.01
COV	0.033	0.031

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639 6.4 Reliability analysis

640 The reliability assessment of the proposed interaction equations was carried out according to
641 Annex D of EN1990 [32] and SEI/ASCE 8-02 [17], and the details are summarised in this
642 section. The material and fabrication uncertainties were given due consideration in the analysis.
643 Afshan et al. [33] proposed statistical data for material parameters to use in reliability
644 calculations in a recent study and these values were adopted in the reliability calculations. The
645 material over-strength factor was taken as 1.3 and 1.1 for austenitic and duplex stainless steel
646 grades, respectively. The values of 0.06 and 0.03 were adopted for the COV of the material
647 strength. The COV of geometric properties was taken as 0.05. Table 18 summarises the key
648 parameters calculated according to EN1990 [32], Annex D to evaluate the reliability of the

649 proposed EN1993-1-3 [12] interaction equation where b is the mean value correction factor,
 650 $k_{d,n}$ is the design fractile factor, V_δ is the coefficient of the variation of the error, and γ_{M1} is the
 651 partial safety factor. The calculated partial safety factor for the proposed interaction equation
 652 is less than the recommended value of 1.1 in EN1993-1-4 [11]. The key parameters calculated
 653 in the reliability analysis for SEI/ASCE 8-02 [17] are given in Table 19 where P_m and V_P are
 654 the mean and the COV of the actual capacity to predicted capacity ratio, respectively, \emptyset is the
 655 resistance factor, and β_0 is the target reliability index. The target reliability index was calculated
 656 considering the data for each stainless steel grade separately. From the calculations, both values
 657 for target reliability index are found to be greater than the recommended value of 3.0 for
 658 structural members in SEI/ASCE 8-02 [17]. Therefore, the proposed interaction equations
 659 satisfy the reliability requirements given in Annex D of EN1990 [32] and SEI/ASCE 8-02 [17].

660 Table 18 Summary of reliability analysis results calculated according to Annex D of EN1990 [32]

	No. of models	b	$k_{d,n}$	V_δ	γ_{M1}
Proposed EN1993-1-3 interaction [12]	24	1.095	3.56	0.080	1.094

661

662 Table 19 Summary of reliability analysis results calculated according to SEI/ASCE 8-02 [17]

Stainless steel grade	No. of models	P_m	V_P	\emptyset	$\beta_0 > 3.0$
Austenitic	12	1.02	0.018	0.85	3.78
Duplex	12	1.01	0.043	0.85	3.02

663

664 7 Concluding remarks

665 This paper discusses the bending and shear interaction behaviour of cold-formed stainless steel
 666 LCB sections which has been given less attention in the past. First, FE models were developed
 667 and validated utilising the experimental results found from the literature for cold-formed
 668 stainless steel and cold-formed steel. The validation included the comparison of ultimate loads,
 669 failure modes and load-deflection curves of three-point and four-point loading tests, and the
 670 FE results were found to be agreed well with the experimental results. Then, a comprehensive
 671 numerical parametric study was conducted employing the validated FE models to extend the
 672 database of cold-formed stainless steel LCBs considering different affecting parameters. This

673 study comprised 60 FE models of three-point loading simulations of stainless steel LCBs with
674 five different aspect ratios to investigate the shear and bending-shear interaction responses
675 while 12 FE models of four-point bending simulations of stainless steel LCBs to study the
676 bending response. Thereafter, the generated numerical database was analysed for the bending-
677 shear interaction of LCBs.

678 The diagonal web shear failure was observed in the sections with an aspect ratio of 1.0. Both
679 local buckling of the compression flanges and the diagonal web shear failure occurred in the
680 sections with aspect ratios of 1.5 and 2.0. The local buckling was taken place in the
681 compression flanges of the sections with higher aspect ratios of 3.0 and 5.0. Therefore, it was
682 concluded that the sections with aspect ratios of 1.5 and 2.0 are subjected to bending-shear
683 interaction.

684 Finally, Eurocode 3 and American specifications interaction equations were evaluated for the
685 bending-shear interaction of cold-formed stainless steel LCB sections using the FE results. It
686 was found that both EN1993-1-3 [12] and SEI/ASCE 8–02 [17] interaction equations are too
687 conservative for a higher level of applied shear force. This is because, the shear resistance of
688 stainless steel LCB sections with shorter spans is not reduced even with a bending moment as
689 high as $1.3 \times M_{f,Rd}$ and this is not taken into consideration in the codified treatment of bending-
690 shear interaction. Therefore, both interaction equations were revised and new interaction
691 equations were proposed using the FE results with aiming to enhance the prediction accuracy.
692 Further, a statistical evaluation was conducted for the proposed interaction equations and
693 assessment of those equations suggested improved and consistent predictions.

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