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Effect of groove spacing on bond strength of near-surface mounted (NSM) bonded joints with multiple FRP strips

Shi Shun Zhang

University of Wollongong, shishun@uow.edu.au

Tao Yu

University of Wollongong, taoy@uow.edu.au

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Abstract

In the strengthening of existing deficient structures using the near-surface mounted (NSM) FRP method, a group of parallel NSM FRP strips are usually needed to meet the capacity enhancement requirement. When the groove spacing (i.e., the net distance between grooves) is relatively small, the bond behaviour of each NSM FRP strip is detrimentally influenced by the adjacent grooves/FRP strips, and such detrimental effect should be taken into account for a safe design of the NSM FRP strengthening system. All the existing models, however, have been proposed for NSM bonded joints with a single FRP strip and thus cannot consider the effect of groove spacing on the bond behaviour, due to the insufficiency of data from tests or numerical simulations. Against this background, a numerical parametric study, was conducted to clarify the effect of groove spacing on the bond strength of such bonded joints; the numerical parametric study involved the use of a three-dimensional meso-scale finite element model developed in the present study for NSM bonded joints with two FRP strips separately embedded in two parallel grooves. Based on the results from the parametric study, a reduction factor to account for the detrimental effect of insufficient groove spacing on the bond strength is proposed and extended to NSM bonded joints with three or more evenly-spaced FRP strips. By combining the proposed reduction factor and the bond strength model previously developed by the authors for NSM bonded joints with a single FRP strip, a bond strength model for NSM bonded joints with multiple FRP strips is proposed and the accuracy of the proposed model is verified with test results.

Keywords

groove, effect, multiple, joints, bonded, (nsm), mounted, near-surface, strips, strength, frp, bond, spacing

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Effect of Groove Spacing on Bond Strength of Near-Surface Mounted (NSM) Bonded Joints with Multiple FRP Strips

S.S. Zhang^{1,*} and T. Yu²

Abstract: In the strengthening of existing deficient structures using the near-surface mounted (NSM) FRP method, a group of parallel NSM FRP strips are usually needed to meet the capacity enhancement requirement. When the groove spacing (i.e., the net distance between grooves) is relatively small, the bond behaviour of each NSM FRP strip is detrimentally influenced by the adjacent grooves/FRP strips, and such detrimental effect should be taken into account for a safe design of the NSM FRP strengthening system. All the existing models, however, have been proposed for NSM bonded joints with a single FRP strip and thus cannot consider the effect of groove spacing on the bond behaviour, due to the insufficiency of data from tests or numerical simulations. Against this background, a numerical parametric study, was conducted to clarify the effect of groove spacing on the bond strength of such bonded joints; the numerical parametric study involved the use of a three-dimensional meso-scale finite element model developed in the present study for NSM bonded joints with two FRP strips separately embedded in two parallel grooves. Based on the results from the parametric study, a reduction factor to account for the detrimental effect of insufficient groove spacing on the bond strength is proposed and extended to NSM bonded joints with three or more evenly-spaced FRP strips. By combining the proposed reduction factor and the bond strength model previously developed by the authors for NSM bonded joints with a single FRP strip, a bond strength model for NSM bonded joints with multiple FRP strips is proposed and the accuracy of the proposed model is verified with test results.

Keywords: concrete; fiber-reinforced polymer (FRP); strip; near-surface mounted (NSM); groove spacing; finite element (FE) model; bond strength model

¹Lecturer, School of Civil, Mining and Environmental Engineering, Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, NSW 2522, Australia (corresponding author). E-mail address: shishun@uow.edu.au.

²Senior Lecturer, School of Civil, Mining and Environmental Engineering, Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, NSW 2522, Australia.

37 1 INTRODUCTION

38 The near-surface mounted (NSM) fiber-reinforced polymer (FRP) strengthening technique, as
39 a promising alternative to the externally bonded (EB) FRP method for structural strengthening,
40 has attracted worldwide attention over the last decade. Compared with the EB FRP method,
41 the NSM FRP method has a number of advantages, including a higher bonding efficiency and
42 a better protection of the FRP reinforcement [1]. FRP bars of various cross-sectional shapes
43 (e.g. square, round and rectangular bars) have been studied by researcher as NSM FRP
44 reinforcement. Existing experimental studies have showed that compared with other
45 cross-sectional shapes, FRP strips (i.e., rectangular bars with a large aspect ratio) possesses a
46 much better bonding efficiency (i.e., a higher local bond strength and a higher interfacial
47 fracture energy), as they have a larger perimeter-to-cross-sectional area ratio and a larger
48 embedment depth [e.g. 2-5]. In terms of material type, carbon FRP (CFRP) are thought to be
49 more attractive than other types of FRP for the application of NSM strengthening technique,
50 as CFRP usually has a higher strength and stiffness and thus could lead to a small
51 cross-sectional area with the same demand in load-carrying capacity. Therefore, CFRP strips
52 have become very popular for the use in NSM FRP strengthening and have attracted a large
53 number of studies [e.g. 1, 5-7]. As one of the fundamental issues in the application of NSM
54 FRP strengthening method, the bond strength, which is the maximum force that can be
55 developed in the FRP reinforcement in the test of bonded joints [e.g. 8, 9], has been studied
56 by a number of researchers, and several bond strength models have been proposed for NSM
57 FRP-to-concrete interfaces by directly regressing test results on NSM FRP-to-concrete
58 bonded joints [e.g. 10, 11] or conducting a numerical parametric study [e.g. 12, 13]. All the
59 existing models, however, were proposed for a single FRP strip NSM to concrete and thus
60 have not taken into account the effect of groove spacing (i.e., the net distance between
61 grooves a_g , as shown in Fig. 1) on the bond behaviour. In real application of NSM FRP

62 strengthening method, including flexural strengthening and shear strengthening of RC
63 members, a group of parallel NSM FRP strips (as shown in Fig. 1) need to be applied to meet
64 the capacity enhancement requirement, and their bond behaviour may be detrimentally
65 influenced by the adjacent grooves/FRP strips. The detrimental effect of insufficient groove
66 spacing on the bond behaviour between NSM FRP reinforcement and concrete has not yet
67 been clarified.

68

69 **2 DETRIMENTAL EFFECT OF INSUFFICIENT GROOVE SPACING**

70 When a group of two FRP strips (separately embedded in two parallel grooves) are used in
71 the NSM strengthening method, the detrimental effect of insufficient groove spacing on the
72 bond behaviour of each FRP strip only exists on the side where the adjacent FRP strip
73 (referred to as adjacent FRP side for simplicity) is embedded. The bond behaviour on the
74 other side (referred to as outer side for simplicity) is free from such detrimental effect, and
75 thus the bond strength contributed from the outer side can be assumed to be half of the bond
76 strength of NSM bonded joints with a single FRP strip. The difference between the total bond
77 strength of each FRP strip and the bond strength contributed from the outer side is just the
78 bond strength contributed from the adjacent FRP side. A reduction factor to account for such
79 effect on the bond strength can therefore be obtained, i.e., the ratio between the bond strength
80 from the adjacent FRP side and half of the bond strength of NSM bonded joints with a single
81 FRP strip. This reduction factor can be extended to situations where a group of three or more
82 FRP strips (embedded in evenly-spaced parallel grooves) are used. Among these FRP strips,
83 each of the two outmost FRP strips suffers the detrimental effect of insufficient groove
84 spacing from one side and thus the reduction factor only needs to be applied on one side in
85 the calculation of the bond strength of each FRP strip, while each of the inner FRP strips
86 suffers such detrimental effect from both sides and thus the reduction factor needs to be

87 applied on both sides in the calculation of the bond strength of each FRP strip.

88

89 Against the above background, a three-dimensional (3-D) meso-scale finite element (FE)
90 model of bonded joints with two CFRP strips is developed, based on the FE model
91 established by Teng *et al.* [14] for bonded joints with a single CFRP strip whose accuracy has
92 been verified with experimental results. A numerical parametric study, covering the most
93 important parameters, is conducted in the present paper by adopting the developed FE model.
94 Based on the results of the parametric study, a reduction factor is proposed to account for the
95 effect of groove spacing on the bond strength. By introducing the proposed reduction factor
96 into the bond strength model previously proposed by the authors (Zhang *et al.* 2014) for
97 bonded joints with a single FRP strip, a new bond strength model is established for bonded
98 joints with multiple FRP strips. The performance of the new bond strength model is then
99 assessed with the existing test results.

100 **3 FINITE ELEMENT (FE) MODEL**

101 **3.1 General**

102 Based on the 3-D meso-scale model developed by Teng *et al.* [14] for the single-lap shear test
103 of NSM FRP strips-to-concrete bonded joints (referred to as NSM bonded joints hereafter for
104 simplicity) with a single FRP strip, the FE model for NSM bonded joints with two FRP strips
105 separately embedded in two parallel grooves (referred to as NSM bonded joints with two FPP
106 strips hereafter for simplicity) was built in the present study, using the software package
107 MSC.MARC [15]. It has been proved that the FE model established by Teng *et al.* [14] can
108 well predict the failure process and ultimate load of NSM bonded joints with a single FRP
109 strip, as well as the strain distributions of the FRP and the local bond-slip relationship
110 between NSM FRP strip and concrete [14]. The failure mechanism of the current case is the
111 same as that modelled in [14], with the only difference being that two FRP strips instead of

112 one need to be included in the built FE model. Failure of NSM bonded joints may happen in
113 the materials (i.e., FRP, adhesive and concrete) or at FRP-to-adhesive/concrete-to-adhesive
114 interfaces [13, 14]. However, it has been widely accepted that in practical applications, it
115 should be guaranteed that the final failure is controlled by the failure in concrete as otherwise
116 the strengthening efficiency cannot be maximized. Existing experimental studies, in fact,
117 have proved that cohesive failure in concrete can be ensured by using an appropriate adhesive
118 (usually with a tensile strength much higher than the concrete) and by carrying out
119 appropriate surface preparation before application [13]. Therefore, in the numerical
120 simulation of NSM bonded joints, the accurate modelling of concrete material is of critical
121 importance. Following Teng *et al.* [14], the modelling of concrete, in particular the tensile
122 and shear behavior of the cracked concrete, was carefully treated in the present study. The
123 well-established tension-softening curve and the shear retention factor model for cracked
124 concrete were incorporated into the FE model through user-defined subroutines.

125 **3.2 FE model and boundary conditions**

126 The schematic of the NSM bond joints with two parallel FRP strips modelled in the present
127 study is shown in Fig. 2. The specimens have a height of 150 mm and a total length of 550
128 mm. The bond length of the FRP is 450mm, which is longer than the effective bond length
129 according to Zhang *et al.* [13] and Seracino *et al.* [9]. A length of 75 mm is left near the
130 loaded end to avoid local shear failure at loaded end, while a length of 25 mm is left near the
131 free end of the FRP strip. The concrete edge distances (i.e., a_e in Figs. 1 and 2, the distance
132 between the outmost groove and the nearer edge of the concrete) in the specimen is changed
133 according to the height of the FRP strip, which will be introduced in details later in the
134 parametric study. Only half of the specimen is included in the FE model (Fig. 2), by taking
135 advantage of symmetry. In addition, the bottom layer of concrete block with a height of 50
136 mm was not included in the FE model. Such simplification has only marginal effect on the

137 modeling accuracy but can significantly save the computational time [14]. The applied
138 boundary conditions include (Fig. 2): (1) the displacements in the width direction of the
139 specimen are prevented on the plane of symmetry; (2) the lower portion (with a height of 50
140 mm) of the vertical surface of the concrete block at the loaded end is restrained in the length
141 direction of the specimen; and (3) the displacement of bottom surface of the concrete block in
142 the vertical direction is restrained. First-order solid elements, which have eight nodes and full
143 Gaussian integration scheme, are used to model the concrete block, the CFRP strip and the
144 adhesive. Interfacial elements between NSM FRP and concrete are not necessary in the
145 present study, as the 3-D meso-scale FE model is able to accurately capture the debonding
146 process by using very small elements [14]. Following Teng *et al.* [14], very fine mesh with an
147 element size in the order of 1 mm are employed in building the FE model.

148 **3.3 Constitutive models**

149 The orthogonal fixed smeared crack model, which is available in MSC.MARC [15], is used
150 to model the cracked concrete. For orthogonal fixed smeared crack model, a maximum of
151 three cracks could occur at each integration point, with their directions being orthogonal to
152 each other. To eliminate the problem of mesh sensitivity, the crack band model proposed by
153 Bazant and Oh [16] is adopted in the FE model, and the tensile fracture energy of cracked
154 concrete given by CEB-FIP [17] is adopted. The yield law proposed by Buyukozturk [18] is
155 used to describe the compression-dominated behaviour of concrete (with the associated flow
156 rule), with the stress-strain behaviour being defined by the Elwi and Murray's [19]
157 compressive stress-strain curve for concrete. The initiation of cracking is detected by the
158 maximum tensile stress criterion. Hordijk's [20] exponential softening curve is used to model
159 tension-softening behavior of cracked concrete, and Okamura and Maekawa's [21] model is
160 used to describe the shear stress-slip behavior of cracked concrete. Both adhesive and FRP
161 are assumed to be isotropic elastic materials. The simplification in the modelling of FRP and

162 adhesive was found to have nearly no effect in such simulation [14]. For more details of the
163 adopted constitutive models, the readers are referred to Teng *et al.* [14] or Zhang and Teng
164 [22, 23].

165 **4 DESIGN OF PARAMETRIC STUDIES**

166 **4.1 Significance analysis of parameters**

167 Before the above built FE model to be employed in the parametric study to investigate the
168 effect of groove spacing on the bond strength, an analysis of the involved parameters should
169 be carried out to identify the significant factors for the present study.

170

171 As the cohesion failure in the concrete near the epoxy-to-concrete interface is the failure
172 mode of interest in the present study, the strength of concrete (f_c) is obviously one of the
173 most important parameter in determining the bond strength. A higher strength of concrete
174 gives a higher fracture energy of concrete and thus a larger bond strength. The groove
175 dimensions also have significantly effect on the bond behaviour: a deeper groove leads to a
176 larger embedment depth of the FRP strip and thus a higher confinement from the surrounding
177 concrete to the FRP strip can be expected. Therefore, the aspect ratio of the groove (i.e., the
178 groove height h_g to groove width w_g ratio) should be important in determining the bond
179 behavior and thus should be included in the parametric study. The thickness of the FRP strip
180 is chosen to be 2 mm (a typical value for commercial CFRP strips), while the height of FRP
181 strip varies in the parametric study to achieve various heights of the groove. The elastic
182 modulus of the CFRP strip in the longitudinal direction is chosen to be 150 GPa (a typical
183 value for pultruded CFRP strips).

184

185 As the adhesive was assumed to be linear-elastic material, the slip between FRP and concrete

186 under a certain local bond stress is only dependent on the thickness and the shear modulus of
187 the adhesive layer. It has been reported by Zhang *et al.* [12] that for commonly used
188 adhesives in NSM CFRP strengthening technique (with an elastic modulus not larger than 5
189 GPa), the adhesive thickness, which varies in the practical range (e.g. around 1-4 mm), has
190 only marginal effect on the slip between the NSM FRP and concrete, as most slip is
191 contributed by the concrete layer adjacent to the concrete-to-adhesive interface. In the present
192 study, the elastic modulus and the thickness of adhesive are taken to be 3 GPa and 2 mm
193 respectively (both are typical values in practice).

194

195 Existing studies have shown that the bond strength of NSM bonded joint increases with the
196 bond length, until the bond length reaches a threshold value. The threshold value of the bond
197 length has been commonly referred to as the effective bond length (L_e) [8]. When the bond
198 length is larger than the effective bond length, any further increase in the bond length does
199 not lead to a further increase in the bond strength. In the present study, the bond length was
200 chosen to be 450 mm, which is sufficiently large to eliminate its detrimental effect on the
201 bond strength, based on Zhang *et al.* [13] and Seracino *et al.* [9]. Furthermore, the bond
202 strength of an NSM bonded joint can be also affected by concrete edge distances (i.e., a_e in
203 Figs. 1 and 2). In the present study, to eliminate the detrimental effect of edge distance on the
204 bond strength, sufficiently large values of concrete edge distance are chosen based on the
205 height of FRP strip, according to Zhang *et al.* [12].

206 **4.2 Numerical specimens in the parametric study**

207 Based on the above considerations, the numerical specimens examined in the parametric
208 study are designed and listed in Table 1. A total of 45 specimens are analyzed in the
209 parametric study, with studied parameters covering the concrete strength, the height-to-width
210 ratio of the groove, and groove spacing. Three values of the cylinder compressive strength of

211 concrete are used respectively: 20 MPa, 30 MPa and 40 MPa; three groove height-to-width
212 ratios are considered respectively: 2.33, 4.00 and 5.67. The groove height-to-width ratios are
213 achieved by changing the height of the grooves with the same width being used for all
214 numerical specimens. The width of the groove is 6 mm, which is the summation of the
215 thickness of CFRP strip (2mm) and the thickness of the adhesive layer (2mm on each side of
216 the strip). The heights of the grooves are 14 mm, 24 mm and 34 mm respectively for CFRP
217 strips with a height of 10 mm, 20 mm and 30 mm, as a 2mm-thick adhesive layer exists on
218 the top as well as the bottom of the strip. The maximum value of 34 mm is chosen based on
219 the consideration that the concrete cover thickness is not much larger than 35 mm in most
220 practical cases, while the minimum value of 14 mm corresponds to FRP strips with a
221 height-to-thickness ratio of 5, which is the lower bound for CFRP strips suggested by Zhang
222 *et al.* [12]. For each of the nine combinations of concrete strength and groove height-to-width
223 ratio, five values of groove spacing are chosen based on the height of the FRP strip: 0 mm,
224 20mm, 40mm, 60mm and 80 mm for bond joints with NSM FRP strips with a height of
225 10mm; 0 mm, 30mm, 60mm, 90mm and 120mm for bond joints with NSM FRP strips with a
226 height of 20mm; and 0 mm, 40mm, 80mm, 120mm and 160mm for bond joints with NSM
227 FRP strips with a height of 30mm. The value of 0mm of the groove spacing refers to the
228 special case in which the two FRP strips are bonded together to form a compound strip whose
229 thickness is twice of the original ones. As shown in Table 1, the name of each numerical case
230 starts with a letter “C”, followed by a letter “f” and a Roman numeral to represent the
231 concrete strength (f_c), a letter “h” and a Roman numeral to represent the height of the CFRP
232 strip (h_f), and two letters “ag” and a Roman numeral to represent the groove spacing (a_g).
233 For instance, Case-f20-h10-ag20 refers to the specimen which has a concrete strength of 20
234 MPa, a FRP strip height of 10 mm and a groove spacing of 20 mm.

235 **5 RESULTS OF PARAMETRIC STUDY**

236 **5.1 Failure process**

237 The Specimen Case-f20-h10-ag60 is selected as an example to demonstrate the predicted
238 typical failure process of bonded joints with two FRP strips, as shown in Fig. 3, in which the
239 distribution of maximum principal cracking strains in the concrete are plotted. It can be seen
240 from Fig. 3, at the initial stage of loading, only a few cracks develop in a very small region
241 near the loaded end while most of the concrete block is still in the elastic range (Fig. 3a).
242 With the increase of the applied load, the width of cracks becomes larger (identified by the
243 color of the plotted maximum principal cracking strain) and the crack region extends in a
244 stereoscopic manner (Fig. 3b). Transverse cracks (i.e., in the plane perpendicular to the load
245 direction) form in the concrete between the two parallel grooves. These cracks are almost
246 vertical within a small layer of the concrete near the top surface of the specimen and become
247 inclined to the horizontal at an angle of around 45 degree when the depth increases. On the
248 other side of the groove (i.e., outside the region sandwiched by the two grooves), the
249 fish-spine-like cracks (i.e., cracks at around 45 degree to the loading direction) appear on the
250 top surface of the specimen. The discrepancies in the crack patterns on the two sides of the
251 groove reveal that the stress states in the concrete on the two sides of the groove are
252 significantly different from each other. This further indicates that interaction between the two
253 grooves exists during the loading process, which influences the behavior of concrete in
254 between. With the further increase in the applied load, more cracks form and the cracking
255 region gradually propagates along the bondline to the free end of NSM FRP strips (Fig. 3c).
256 At the final stage, the cracking region takes up around 60% of the bond length and does not
257 reach the edge of the concrete block (Fig. 3d), indicating that the bond length and edge
258 distance chosen for the specimen are sufficiently large to prevent their detrimental effects on
259 the bond strength. It can be clearly seen from Fig. 3d that most transverse cracks in the

260 concrete sandwiched by the two grooves connect with adjacent ones at a depth of the groove
261 height, resulting in a big horizontal crack on the plane passing through the bottom surface of
262 the groove. This horizontal crack means that the concrete sandwiched by the two grooves is
263 pulled out with the two FRP strips, which agree well with the experimental observations
264 made by Rashid *et al.* [24].

265 **5.2 Bond strength**

266 As only half of the specimen was included in the FE modelling by taking advantage of
267 symmetry, the bond strength of the whole specimen was obtained by multiplying the ultimate
268 load directly obtained from the FE modelling by 2. The bond strengths obtained from the
269 parametric study are listed in Table 2, and the relationships between the bond strength and
270 groove spacing are plotted in Fig. 4.

271

272 It can be seen from Fig. 4 that: (1) a larger concrete strength or a larger height of FRP strip
273 gives a larger bond strength of the specimen, which agrees with the findings for bonded joint
274 with a single FRP strip [13]; (2) the bond strength increases with the value of groove spacing
275 but the increasing rate decreases largely with the value of groove spacing. When the value of
276 groove spacing is larger than a certain value, further increase in the groove spacing gives
277 marginal if not no increase in the bond strength. It can be seen from Table 2 that, for all
278 studied series of numerical specimens, the bond strength of the specimens with the largest
279 value of groove spacing studied in that series is very close to that with the second largest
280 groove spacing, indicating that the value of bond strength has been converged with respect to
281 the value of groove spacing.

282 **5.3 Threshold value of groove spacing**

283 In the present study, the minimum required value of groove spacing for the full development
284 of bond strength of the bonded joint with two FRP strips is termed as the threshold value of

285 groove spacing (i.e., a_{gt} in Table 2). The threshold value of groove spacing listed in Table 2
286 are obtained using the following steps: (1) for each of the nine series of the numerical
287 specimens, find the best-fit four-order polynomial function to describe the relationship
288 between the bond strength and the value of groove spacing; (2) use the obtained best-fit
289 four-order polynomial function to calculate the value of groove spacing which corresponds to
290 99% of the bond strength obtained with the largest groove spacing in that series, and this
291 groove spacing value is treated as the threshold value of groove spacing in the present study.
292 The threshold values of groove spacing obtained using this method are listed in Table 2.

293

294 It can be seen from Table 2 that a larger groove height (i.e., a larger FRP height) or a higher
295 concrete strength leads to a larger threshold value of groove spacing, which is not difficult to
296 understand: a deeper groove or a higher strength of concrete usually incurs a larger motivated
297 stress zone around the groove and consequently a larger overlapping zone of the stress for a
298 given value of groove spacing. To find the calculation equation for the threshold value of
299 groove spacing, firstly, the relationship between the threshold value of groove spacing and
300 the groove height is plotted in Fig. 5a, in which the best-fit power functions are also shown. It
301 can be seen from Fig. 5a that the relationship between the threshold value of groove spacing
302 and the groove height can be described by the following power function:

$$303 \quad a_{gt} = A \times h_g^B \quad (1)$$

304 where the coefficient A and the power B are related to the concrete strength f_c . The
305 relationship between the coefficient A and the concrete strength is shown in Fig. 5b, and the
306 relationship between the power B and the concrete strength is shown in Fig. 5c. Based on the
307 best-fit curves shown in Figs. 5b and 5c, two linear functions are respectively proposed for
308 the coefficient A and the power B :

$$309 \quad A = 0.046 f_c + 3.07 \quad (2)$$

310
$$B = -0.002 f_c + 1.03 \quad (3)$$

311 The predictions of the threshold value of groove spacing from Eq. (1) are compared with the
 312 results from the FE analysis (see Table 2) in Fig. 5d, from which close agreement can be
 313 observed. It can be seen from Table 2 that the ratios between predictions of Eq. (1) and FE
 314 analysis have an average value of 1.003, a standard deviation (STD) of 0.024, and a
 315 coefficient of variation (CoV) of 0.023.

316 **5.4 Reduction factor β_g accounting for the effect of groove spacing**

317 As can be seen from the parametric study, when the groove spacing is smaller than the
 318 threshold value, interaction between adjacent grooves/FRP strips exists and as a result, the
 319 maximum load \overline{P}_u that could be resisted by each FRP strip in bonded joints with multiple
 320 FRP strips will be smaller than the bond strength of NSM bonded joints with a single FRP
 321 strip P_u . To account for this detrimental effect on the bond strength, a reduction factor β_g
 322 needs to be introduced as

323
$$\overline{P}_u = \beta_g P_u \quad (4)$$

324 In the present study, it is assumed that \overline{P}_u is equal to P_u when the groove spacing reaches
 325 the threshold value a_{gt} . To get β_g , for each studied series in the parametric study, the
 326 threshold value of groove spacing and the corresponding bond strength are treated as the
 327 references, with respect to which other groove spacings and bond strengths are normalized
 328 respectively. The normalized bond strength versus the normalized groove spacing curves just
 329 represent the reduction factor β_g and are shown in Fig. 6a, from which it can be seen that
 330 although the curves do not perfectly coincide with each other, the scatter is very small. By
 331 regressing all the points on Fig. 6a, the following equation is proposed for the reduction
 332 factor β_g :

333
$$\beta_g = -0.23 \left(\frac{a_g}{a_{gt}} \right)^2 + 0.51 \left(\frac{a_g}{a_{gt}} \right) + 0.72 \leq 1 \quad (5)$$

334 Although Eq. (5) can give accurate prediction of the reduction factor, its form is relatively
 335 complex. Therefore, a simplified reduction factor, described by linear function expressed in
 336 Eq. (6), is also proposed and assessed in the present study.

337
$$\beta_g = 0.72 + 0.28 \left(\frac{a_g}{a_{gt}} \right) \leq 1 \quad (6)$$

338 Fig. 6b shows the comparison of predictions given by Eq. (5) and Eq. (6). It can be seen from
 339 Fig. 6b that the simplified reduction factor (Eq. 6) is close to and consistently lower than the
 340 accurate reduction factor (Eq. 5).

341

342 It should be noted that the β_g in Eq. (5) or (6) is only applicable for FRP strips in bonded
 343 joints with two FRP strips and the two outmost FRP strips in bonded joints with three or more
 344 FRP strips (i.e., the detrimental effect caused by an insufficient groove spacing only exists on
 345 one side of the FRP strip). For FRP strips suffering the detrimental effect from both sides,
 346 such as the inner FRP strips in bonded joints with three or more FRP strips, the reduction
 347 factor β_{g_in} can be obtained through the following analysis.

348

349 For FRP strips which have adjacent FRP strip on one side but not on the other side, the
 350 ultimate load that can be resisted by the FRP strip is given by

351
$$\overline{P}_u = P_{u1} + P_{u2} \quad (7)$$

352 Where P_{u1} is the load contributed by the bond from the side in which no adjacent FRP strip
 353 exist, and can be assumed to be half of the bond strength of NSM bonded joints with a single
 354 FRP strip, i.e., $0.5P_u$; and P_{u2} is the load contributed by the bond from the side in which

355 adjacent FRP strip exists, and can be expressed as $\beta_{g_in} \times (0.5P_u)$. Therefore, Eq. (7) can be
 356 expressed as

$$357 \quad \overline{P_u} = 0.5P_u + 0.5\beta_{g_in}P_u \quad (8)$$

358 Combining Eqs. (4) and (8) gives:

$$359 \quad \beta_{g_in} = 2\beta_g - 1 \quad (9)$$

360 **5.5 Bond strength model**

361 Based on the above consideration, the bond strength model for bonded joints with multiple
 362 evenly-spaced FRP strips can be expressed as:

$$363 \quad P_{u_m} = \left(2\beta_g + \sum_0^{n-2} \beta_{g_in} \right) P_u \quad (10)$$

364 where n is the number of FRP strips; P_u is the bond strength of NSM bonded joints with a
 365 single FRP strip and can be obtained using the equation proposed by Zhang *et al.* [13]:

$$366 \quad P_u = \sqrt{2G_f E_f A_f C_{failure}} \leq P_t \quad \text{when } L_b \geq L_e \quad (11)$$

$$367 \quad P_u = \beta_L \sqrt{2G_f E_f A_f C_{failure}} \leq P_t \quad \text{when } L_b < L_e \quad (12)$$

$$368 \quad G_f = 0.40\gamma^{0.422} f_c^{0.619} \quad (13)$$

$$369 \quad L_e = \frac{1.66}{\eta} \quad (14)$$

$$370 \quad \eta^2 = \frac{\tau_{max}^2 C_{failure}}{2G_f E_f A_f} \quad (15)$$

$$371 \quad \tau_{max} = 1.15\gamma^{0.138} f_c^{0.613} \quad (16)$$

$$372 \quad \beta_L = \frac{L_b}{L_e} (2.08 - 1.08 \frac{L_b}{L_e}) \quad (17)$$

373 where A_f (mm²) is the cross sectional area of a single FRP strip; $C_{failure}$ (mm) is taken to be
 374 the sum of the three side lengths of the groove; E_f (MPa) is the elastic modulus of the FRP

375 strip; f_c (MPa) is the compressive strength of concrete cylinder; G_f (N/mm) is the
376 interfacial fracture energy; L_b (mm) is the bond length; L_e (mm) is the effective bond length;
377 P_t (N) is the full tensile capacity of a single FRP strip; τ_{\max} (MPa) is the maximum bond
378 stress, γ is the groove height-to-width ratio, β_L the a reduction factor to consider the
379 detrimental effect of insufficient bond lengths.

380 **6 VERIFICATION OF THE PROPOSED BOND STRENGTH MODEL**

381 **6.1 Comparison with FE results**

382 The comparison of bond strength between the prediction of Eq. (10) and FE results for the 45
383 numerical specimens (see Table 2) are listed in Table 3 and plotted in Fig. 7. It can be seen
384 from Table 3 that, if the detrimental effect of groove spacing is ignored (i.e., the reduction
385 factor is set to 1.0), the proposed bond strength model overestimates the FE results with an
386 average prediction-to-FE load ratio of 1.142, and the scatter of the prediction is relatively
387 large with a STD of 0.152 and a CoV of 0.133. If the accurate reduction factor (Eq. 5) is
388 adopted, the performance of the proposed bond strength model is largely improved, with the
389 average, STD and CoV of prediction-to-FE load ratio being 1.017, 0.011 and 0.011
390 respectively. It can be also seen form Table 3 that the proposed bond strength model with the
391 simplified reduction factor (Eq. 6) can give similarly accurate prediction to that with the
392 accurate reduction factor (Eq. 5), with the average, STD and CoV of prediction-to-FE load
393 ratio being 1.008, 0.050 and 0.050 respectively. The better performance of the bond strength
394 model with either the accurate reduction factor or the simplified reduction factor can be also
395 evidenced by the much smaller scatter of the points plotted in Fig. 7: the points predicted by
396 either the accurate reduction factor or the simplified reduction factor are very close to the
397 diagonal line (i.e., $y=x$), while most points predicted without considering the detrimental
398 effect of groove spacing are far away from the diagonal line.

399 **6.2 Comparison with test results**

400 By far, a large number of experimental studies have been conducted on the bond strength of
401 NSM bonded joints [13], but most studies are for bonded joints with a single FRP strip. To
402 the best knowledge of the authors, so far the only experimental study (published in English)
403 on bonded joints with two FRP strips is from Rashid *et al.* [24]. There have been studies on
404 RC flexural members strengthened with multiple NSM FRP strips, such as the tests on RC
405 girders (recovered from a 42-year-old bridge) strengthened with 8 NSM CFRP strips evenly
406 embedded in 4 grooves [25] and the tests on RC beams strengthened with 8 NSM CFRP
407 strips evenly embedded in 4 grooves [26]. However, no experimental study (published in
408 English) on bonded joints with three or more NSM FRP strips was found in the open
409 literature. In Rashid *et al.*'s [24] tests, two parallel CFRP strips with an aspect ratio of 16.7
410 (i.e., the height of 20mm and the width of 1.2mm) were used in each specimen, with the
411 groove spacing between them being varied to study its effect on the bond strength. Recently,
412 the authors conducted a series of tests on bonded joints with two parallel CFRP strips to study
413 the effect of groove spacing, using the test setup shown in Fig. 8. In the test, the concrete
414 block has a height of 150mm, a length of 400 mm and a width of 300 mm; the CFRP strip
415 had a height of 16mm, a thickness of 2 mm and a bond length of 350mm; the tensile strength
416 and elastic modulus of the CFRP strips, averaged from three tensile specimens, were found to
417 be 2131 MPa and 123 GPa respectively. The details of all specimens are listed in Table 4.

418

419 The comparison of the bond strength between the prediction from the proposed model (i.e. Eq.
420 10) and test results are listed in Table 4 and plotted in Fig. 9. As can be seen from Table 4, if
421 the detrimental effect of groove spacing is ignored, the proposed bond strength model gives
422 an average value, a STD and a CoV of prediction-to-test load ratio of 0.987, 0.103 and 0.104
423 respectively. If the accurate reduction factor is used to consider such detrimental effect, the

424 performance of the proposed bond strength model is improved as the STD and CoV of
425 prediction-to-test load ratio are reduced to 0.062 and 0.070 respectively. The smaller average
426 prediction-to-test load ratio of 0.889 obtained with the accurate reduction factor does not
427 mean the poor performance of the reduction factor model, in the sense that (1) the smaller
428 average prediction-to-test load ratio is caused by P_u , which was proposed to give a
429 conservative prediction of the test results (see Zhang *et al.* [13]); (2) the average value can be
430 easily increased by introducing an amplifying coefficient into the bond strength model,
431 without influencing the values of STD and CoV which are the more reasonable statistical
432 characteristics to judge the performance of the proposed reduction factor models. Compared
433 with the accurate reduction factor (Eq. 5), the simplified reduction factor (Eq. 6) leads to
434 nearly the same STD and CoV values of prediction-to-test load ratio (0.059 and 0.070
435 respectively), but a slightly smaller average prediction-to-test load ratio of 0.845. The smaller
436 average value of prediction-to-test load ratio is because that the reduction factor predicted by
437 the simplified model (Eq. 5) is always smaller than that by the accurate model (Eq. 6), as
438 shown in Fig. 6. The better performance of the proposed bond strength models with either the
439 accurate reduction factor or simplified reduction factor can be also seen from the smaller
440 scatter of the points and the smaller R-squared values shown in Fig. 9. The above comparison
441 indicates that the proposed model can provide reasonably accurate and conservative
442 predictions of the test results.

443

444 **7 CONCLUDING REMARKS**

445 This paper has been concerned with the adverse effect of groove spacing (i.e., the net distance
446 between grooves) on the bond strength of NSM bonded joints with multiple FRP strips. A
447 3-D meso-scale FE model for NSM bonded joints with two FPP strips separately embedded
448 in two parallel grooves is first established, based on the FE model previously developed by

449 the author [14] for NSM bonded joints with a single FRP strip. The developed FE model is
450 then employed in a numerical parametric study to investigate the reduction of the bond
451 strength of each NSM FRP strip caused by the adverse effect from the adjacent groove. Based
452 on the results from the numerical parametric study, the equation for the threshold value of
453 groove spacing (i.e., the minimum required value of groove spacing for the full development
454 of bond strength of the bonded joint with two FRP strips) is formulated, and the bond strength
455 model for NSM bonded joints with multiple FRP strips is proposed with two reduction
456 factors (an accurate reduction factor and a simplified reduction factor) accounting for the
457 adverse effect of groove spacing being introduced. Based on the findings in the present study,
458 the following conclusions can be drawn:

- 459 (1) The bond strength of each NSM FRP strip in bonded joints with multiple FRP strips can
460 be significantly influenced by the adjacent groove/FRP strip, when the groove spacing is
461 relatively small. When the groove spacing is larger than a threshold value, such
462 detrimental effect on the bond strength does not exist anymore;
- 463 (2) For the parametric combinations studied herein, the threshold value of groove spacing is
464 found to be mainly dependent on the groove height and the concrete strength. In general,
465 a larger groove height or concrete strength leads to a larger threshold value; and
- 466 (3) Comparison of the bond strength between existing FE/test results and predictions of the
467 proposed bond strength model verifies the accuracy of the proposed bond strength model
468 for NSM bonded joints with two FRP strips. More experimental studies, especially on
469 NSM bonded joints with three/more FRP strips, are still in a need for the further
470 verification the proposed model.

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475

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- 543

TABLES

Table 1 Design of parametric study of groove spacing

Specimens	f_c (MPa)	t_f (mm)	h_f (mm)	E_f (GPa)	h_f/t_f	a_e (mm)	a_g (mm)
Case-f20-h10-ag0, 20,40, 60 or 80	20	2	10	150	5	60	0, 20, 40, 60 and 80
Case-f20-h20-ag0, 30, 60, 90, or 120	20	2	20	150	10	100	0, 30, 60, 90, and 120
Case-f20-h30-ag0, 40, 80, 120 or 160	20	2	30	150	15	140	0, 40, 80, 120 and 160
Case-f30-h10-ag0, 20,40, 60 or 80	30	2	10	150	5	60	0, 20, 40, 60 and 80
Case-f30-h20-ag0, 30, 60, 90, or 120	30	2	20	150	10	100	0, 30, 60, 90, and 120
Case-f30-h30-ag0, 40, 80, 120 or 160	30	2	30	150	15	140	0, 40, 80, 120 and 160
Case-f40-h10-ag0, 20,40, 60 or 80	40	2	10	150	5	60	0, 20, 40, 60 and 80
Case-f40-h20-ag0, 30, 60, 90, or 120	40	2	20	150	10	100	0, 30, 60, 90, and 120
Case-f40-h30-ag0, 40, 80, 120 or 160	40	2	30	150	15	140	0, 40, 80, 120 and 160

Table 2 Threshold values of groove spacing

Specimens	Bond strength (kN) with different a_g (mm)					a_{gr} (mm)		
	0mm	20mm	40mm	60mm	80mm	FE analysis	Prediction of Eq. (1)	Prediction / FE analysis
Case-f20-h10-ag0, 20,40, 60 or 80	38.23	46.68	51.94	53.29	53.71	53.4	54.4	1.020
Case-f30-h10-ag0, 20,40, 60 or 80	43.86	53.29	58.91	61.13	61.59	57.2	57.6	1.006
Case-f40-h10-ag0, 20,40, 60 or 80	48.34	58.79	64.94	67.28	67.91	59.1	60.2	1.020
Specimens	Bond strength (kN) with different a_g (mm)					a_{gr} (mm)		
	0mm	30mm	60mm	90mm	120mm			
Case-f20-h20-ag0, 30, 60, 90, or 120	76.04	90.75	100.24	105.21	106.75	95.1	92.8	0.975
Case-f30-h20-ag0, 30, 60, 90, or 120	87.20	105.00	115.59	120.57	122.71	100.8	97.1	0.964
Case-f40-h20-ag0, 30, 60, 90, or 120	96.11	114.04	126.01	132.08	134.78	103.0	100.5	0.976
Specimens	Bond strength (kN) with different a_g (mm)					a_{gr} (mm)		
	0mm	40mm	80mm	120mm	160mm			
Case-f20-h30-ag0, 40, 80, 120 or 160	116.94	139.00	154.39	162.28	164.68	127.4	131.0	1.028
Case-f30-h30-ag0, 40, 80, 120 or 160	134.18	157.61	175.21	185.05	188.79	134.4	136.1	1.013
Case-f40-h30-ag0, 40, 80, 120 or 160	147.89	173.97	192.55	203.44	207.98	136.1	140.0	1.028
Statistical characteristics							Average =	1.003
							STD =	0.024
							CoV =	0.023

Table 3. Bond strength comparison between predictions and FE results

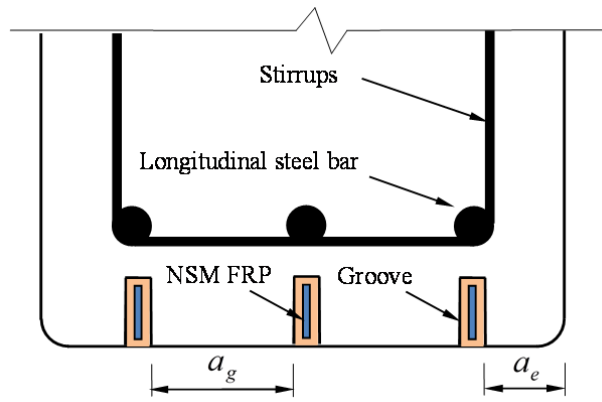
	t_f (mm)	h_f (mm)	w_g (mm)	h_g (mm)	E_f (GPa)	a_g (mm)	f_c (MPa)	FE (kN)	Without reduction factor		With reduction factor given by Eq. (5)		With reduction factor given by Eq. (6)	
									Prediction (kN)	Prediction / FE	Prediction (kN)	Prediction / FE	Prediction (kN)	Prediction / FE
Case-f20-h10-ag0	2	10	6	14	150	0	20	38.23	54.6	1.428	39.3	1.028	39.3	1.028
Case-f20-h10-ag20	2	10	6	14	150	20	20	46.68	54.6	1.170	47.9	1.025	44.9	0.963
Case-f20-h10-ag40	2	10	6	14	150	40	20	51.94	54.6	1.051	53.0	1.020	50.6	0.973
Case-f20-h10-ag60	2	10	6	14	150	60	20	53.29	54.6	1.024	54.6	1.024	56.2	1.054
Case-f20-h10-ag80	2	10	6	14	150	80	20	53.71	54.6	1.017	54.6	1.017	61.8	1.151
Case-f20-h20-ag0	2	20	6	24	150	0	20	76.04	109.0	1.434	78.5	1.032	78.5	1.032
Case-f20-h20-ag30	2	20	6	24	150	30	20	90.75	109.0	1.201	93.9	1.034	88.4	0.974
Case-f20-h20-ag60	2	20	6	24	150	60	20	100.24	109.0	1.088	104.0	1.037	98.2	0.980
Case-f20-h20-ag90	2	20	6	24	150	90	20	105.21	109.0	1.036	108.8	1.035	108.1	1.028
Case-f20-h20-ag120	2	20	6	24	150	120	20	106.75	109.0	1.021	109.0	1.021	118.0	1.105
Case-f20-h30-ag0	2	30	6	34	150	0	20	116.94	168.2	1.439	121.1	1.036	121.1	1.036
Case-f20-h30-ag40	2	30	6	34	150	40	20	139.00	168.2	1.210	143.7	1.034	135.5	0.975
Case-f20-h30-ag80	2	30	6	34	150	80	20	154.39	168.2	1.090	159.1	1.031	149.9	0.971
Case-f20-h30-ag120	2	30	6	34	150	120	20	162.28	168.2	1.037	167.3	1.031	164.3	1.012
Case-f20-h30-ag160	2	30	6	34	150	160	20	164.68	168.2	1.022	168.2	1.022	178.7	1.085
Case-f30-h10-ag0	2	10	6	14	150	0	30	43.86	61.9	1.411	44.6	1.016	44.6	1.016
Case-f30-h10-ag20	2	10	6	14	150	20	30	53.29	61.9	1.162	53.8	1.010	50.6	0.949
Case-f30-h10-ag40	2	10	6	14	150	40	30	58.91	61.9	1.051	59.6	1.012	56.6	0.961
Case-f30-h10-ag60	2	10	6	14	150	60	30	61.13	61.9	1.013	61.9	1.013	62.6	1.025
Case-f30-h10-ag80	2	10	6	14	150	80	30	61.59	61.9	1.005	61.9	1.005	68.7	1.115
Case-f30-h20-ag0	2	20	6	24	150	0	30	87.20	123.6	1.418	89.0	1.021	89.0	1.021
Case-f30-h20-ag30	2	20	6	24	150	30	30	105.00	123.6	1.177	105.8	1.007	99.7	0.949
Case-f30-h20-ag60	2	20	6	24	150	60	30	115.59	123.6	1.069	117.1	1.013	110.4	0.955
Case-f30-h20-ag90	2	20	6	24	150	90	30	120.57	123.6	1.025	123.0	1.020	121.1	1.004
Case-f30-h20-ag120	2	20	6	24	150	120	30	122.71	123.6	1.007	123.6	1.007	131.8	1.074
Case-f30-h30-ag0	2	30	6	34	150	0	30	134.18	190.7	1.421	137.3	1.023	137.3	1.023

Case-f30-h30-ag40	2	30	6	34	150	40	30	157.61	190.7	1.210	162.1	1.029	153.0	0.971
Case-f30-h30-ag80	2	30	6	34	150	80	30	175.21	190.7	1.089	179.3	1.024	168.7	0.963
Case-f30-h30-ag120	2	30	6	34	150	120	30	185.05	190.7	1.031	189.0	1.021	184.4	0.997
Case-f30-h30-ag160	2	30	6	34	150	160	30	188.79	190.7	1.010	190.7	1.010	200.1	1.060
Case-f40-h10-ag0	2	10	6	14	150	0	40	48.34	67.7	1.400	48.7	1.008	48.7	1.008
Case-f40-h10-ag20	2	10	6	14	150	20	40	58.79	67.7	1.151	58.5	0.994	55.0	0.936
Case-f40-h10-ag40	2	10	6	14	150	40	40	64.94	67.7	1.042	64.8	0.997	61.3	0.944
Case-f40-h10-ag60	2	10	6	14	150	60	40	67.28	67.7	1.006	67.6	1.006	67.6	1.005
Case-f40-h10-ag80	2	10	6	14	150	80	40	67.91	67.7	0.996	67.7	0.996	73.9	1.088
Case-f40-h20-ag0	2	20	6	24	150	0	40	96.11	135.1	1.406	97.3	1.012	97.3	1.012
Case-f40-h20-ag30	2	20	6	24	150	30	40	114.04	135.1	1.185	115.1	1.009	108.6	0.952
Case-f40-h20-ag60	2	20	6	24	150	60	40	126.01	135.1	1.072	127.3	1.011	119.9	0.951
Case-f40-h20-ag90	2	20	6	24	150	90	40	132.08	135.1	1.023	134.1	1.015	131.2	0.993
Case-f40-h20-ag120	2	20	6	24	150	120	40	134.78	135.1	1.003	135.1	1.003	142.4	1.057
Case-f40-h30-ag0	2	30	6	34	150	0	40	147.89	208.5	1.410	150.1	1.015	150.1	1.015
Case-f40-h30-ag40	2	30	6	34	150	40	40	173.97	208.5	1.198	176.6	1.015	166.8	0.959
Case-f40-h30-ag80	2	30	6	34	150	80	40	192.55	208.5	1.083	195.2	1.014	183.5	0.953
Case-f40-h30-ag120	2	30	6	34	150	120	40	203.44	208.5	1.025	206.0	1.013	200.2	0.984
Case-f40-h30-ag160	2	30	6	34	150	160	40	207.98	208.5	1.002	208.5	1.002	216.9	1.043
Statistical characteristics									Average =	1.142		1.017		1.008
									STD =	0.152		0.011		0.050
									CoV =	0.133		0.011		0.050

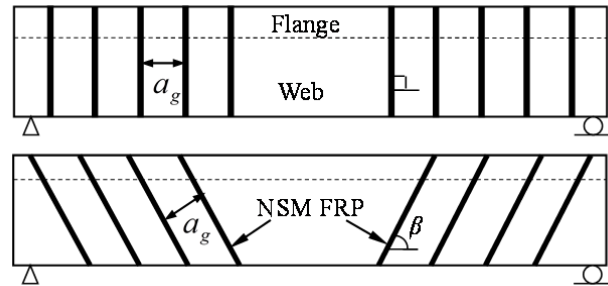
Table 4. Bond strength comparison between predictions and test results

	Specimen	t_f (mm)	h_f (mm)	w_g (mm)	h_g (mm)	E_f (GPa)	a_g (mm)	f_c (MPa)	Test (kN)	Without reduction factor		With reduction factor given by Eq. (5)		With reduction factor given by Eq. (6)	
										Prediction (kN)	Prediction / FE	Prediction (kN)	Prediction / FE	Prediction (kN)	Prediction / FE
Rashid et al. (2008)	G30NSM	1.2	20	3	22	161	30	20	102.3	110.8	1.083	90.0	0.880	90.0	0.880
	G40NSM	1.2	20	3	22	161	40	20	124.3	110.8	0.891	99.7	0.802	93.4	0.751
	G50NSM	1.2	20	3	22	161	50	40	118.5	110.8	0.935	103.1	0.870	96.8	0.817
	G70NSM	1.2	20	3	22	161	70	40	135.5	110.8	0.818	108.1	0.798	103.6	0.765
Tests by the authors	S-30-27	2	16	6	20	123	27	32	82.5	90.9	1.102	78.4	0.951	73.8	0.895
	S-30-54	2	16	6	20	123	54	32	98.2	90.9	0.926	86.9	0.885	82.2	0.837
	S-50-27	2	16	6	20	123	27	58	97.9	109.2	1.115	93.2	0.952	87.9	0.898
	S-50-54	2	16	6	20	123	54	58	106	109.2	1.030	103.2	0.973	97.2	0.917
Statistical characteristics										Average =	0.987		0.889		0.845
										STD =	0.103		0.062		0.059
										CoV =	0.104		0.070		0.070

FIGURES



(a) Flexural strengthening



(b) Shear strengthening

Figure 1. Strengthening of RC beams using NSM FRP method

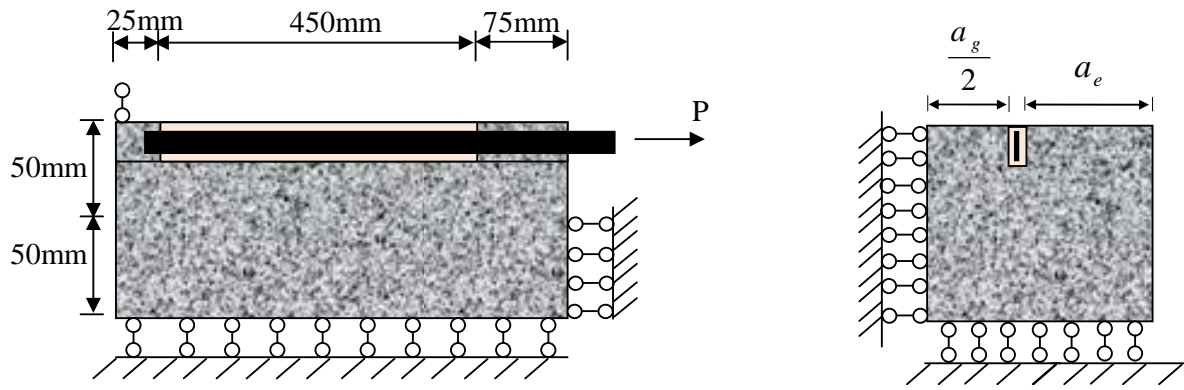
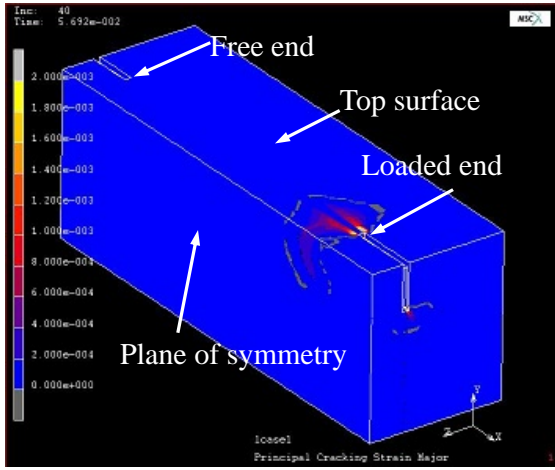
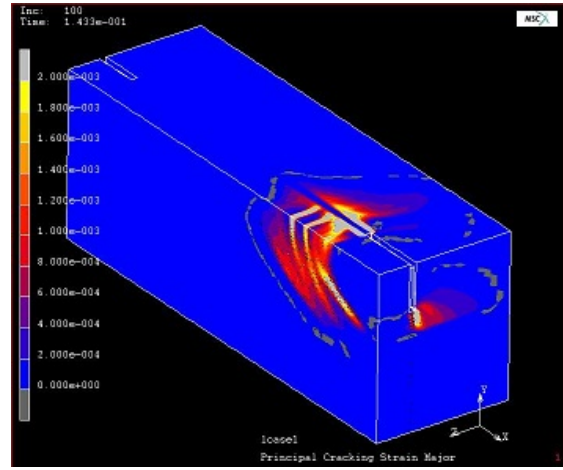


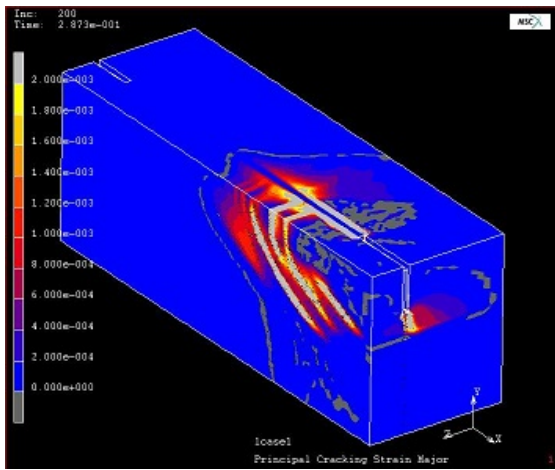
Figure 2. Schematic of the NSM bond joint in parametric studies of the groove spacing



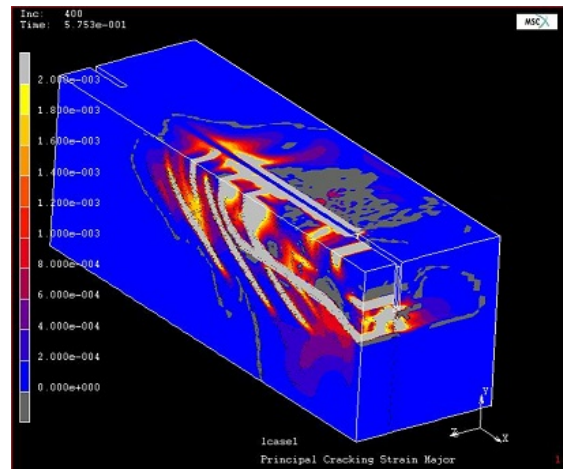
(a)



(b)

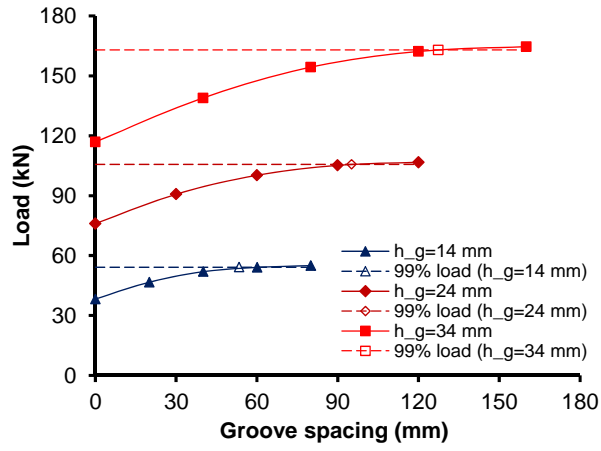


(c)

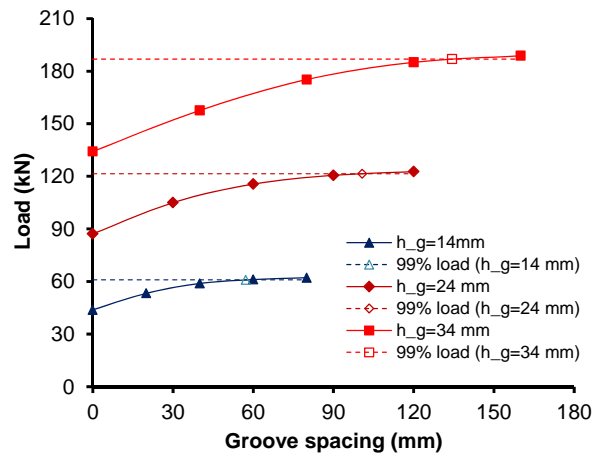


(d)

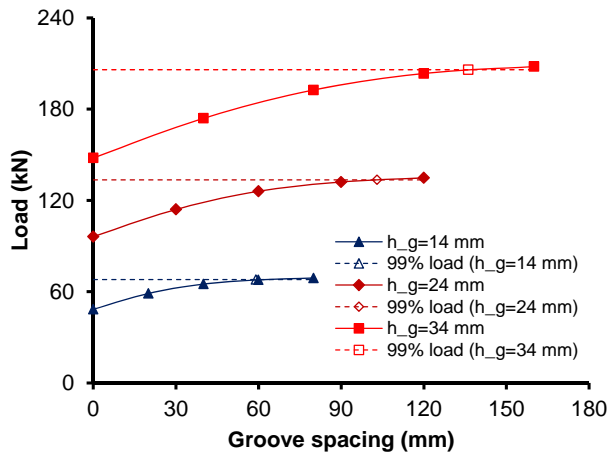
Figure 3. Failure process



a) $f_c = 20$ MPa

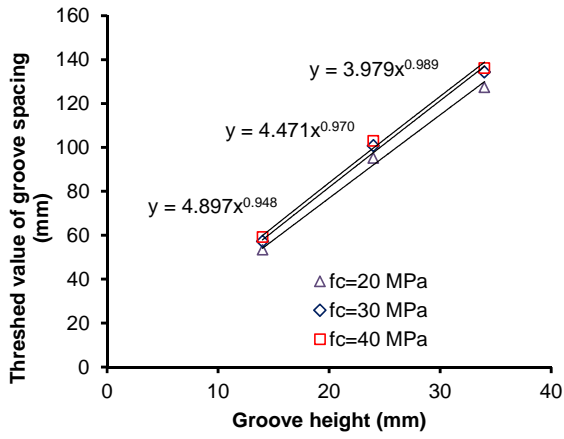


b) $f_c = 30$ MPa

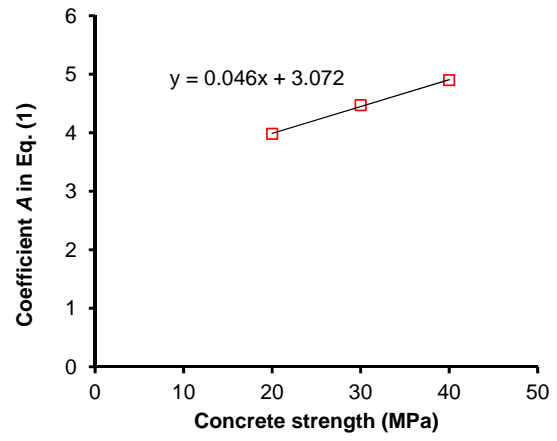


c) $f_c = 40$ MPa

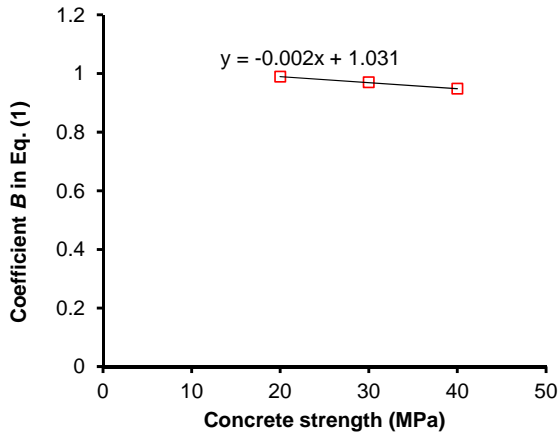
Figure 4. Load versus groove spacing curves



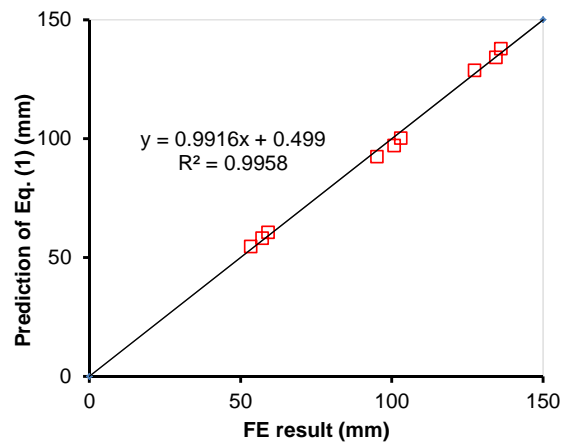
(a) Threshold value versus groove height



(b) Coefficient A in Eq. (1)

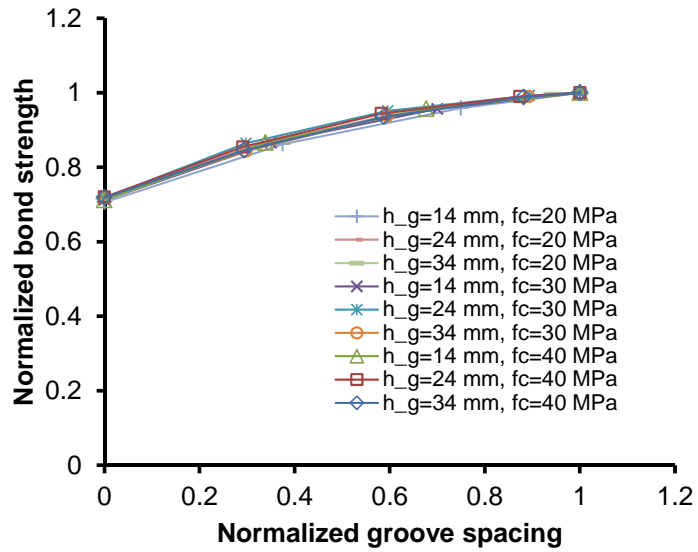


(c) Coefficient B in Eq. (1)

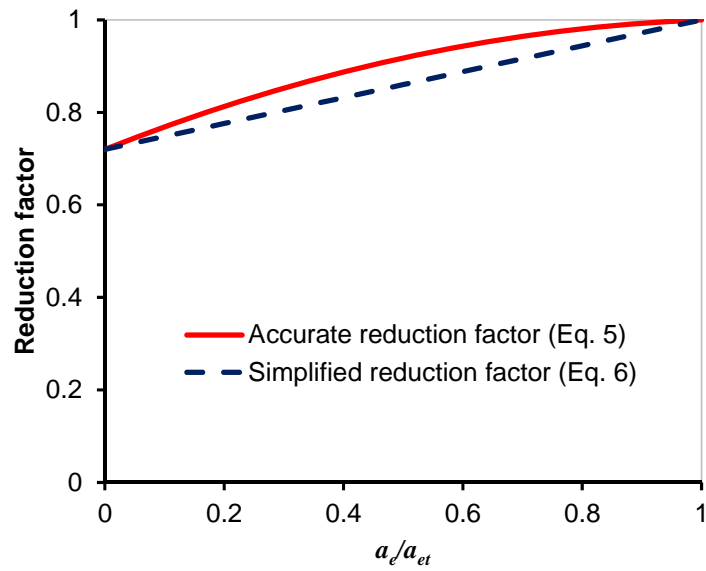


(d) verification of Eq. (1)

Figure 5. The threshold value of groove spacing

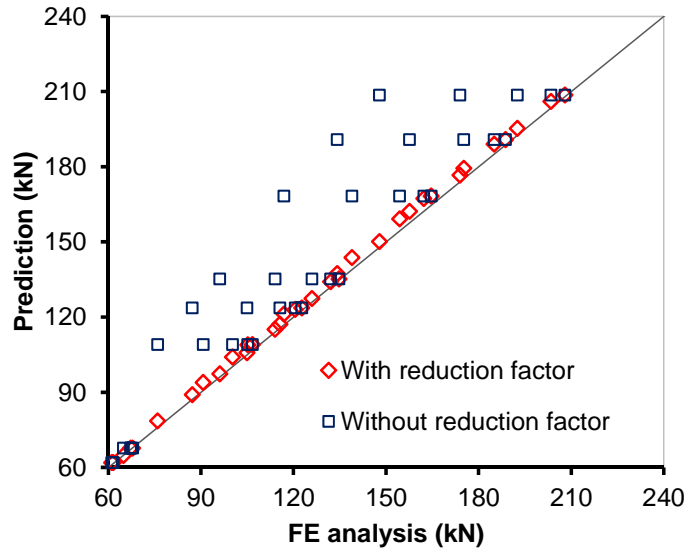


(a) Normalized bond strength versus normalized groove spacing

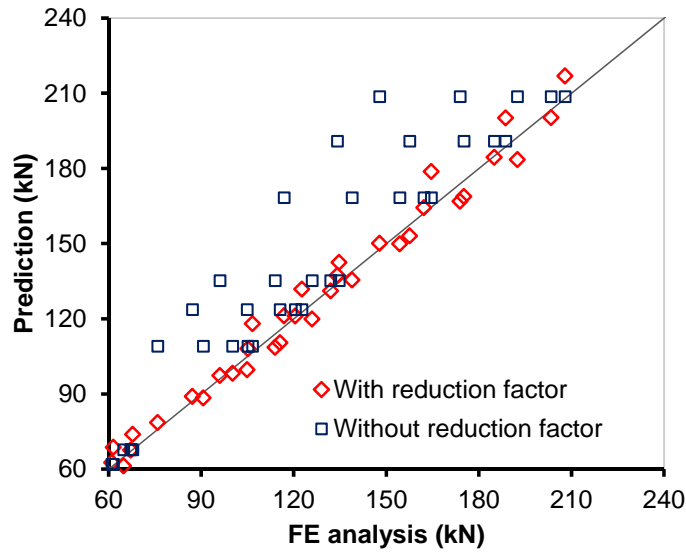


(b) Comparison of the two reduction factor models

Figure 6. Proposed reduction factors: (a) Normalized bond strength versus normalized groove spacing; (b) Comparison of the two reduction factor models

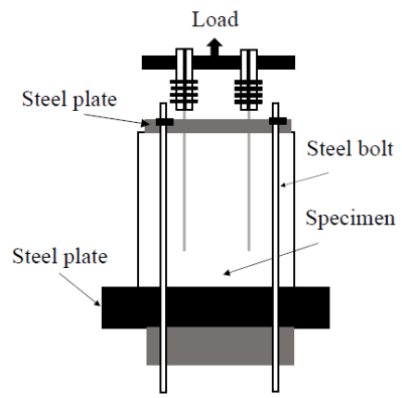


(a) Prediction using the accurate reduction factor (Eq. 5)



(b) Prediction using the simplified reduction factor (Eq. 6)

Figure 7. Comparison of bond strength between predictions and FE results: (a) Prediction using the accurate reduction factor (Eq. 5); (b) Prediction using the simplified reduction factor (Eq. 6)



(a) test setup

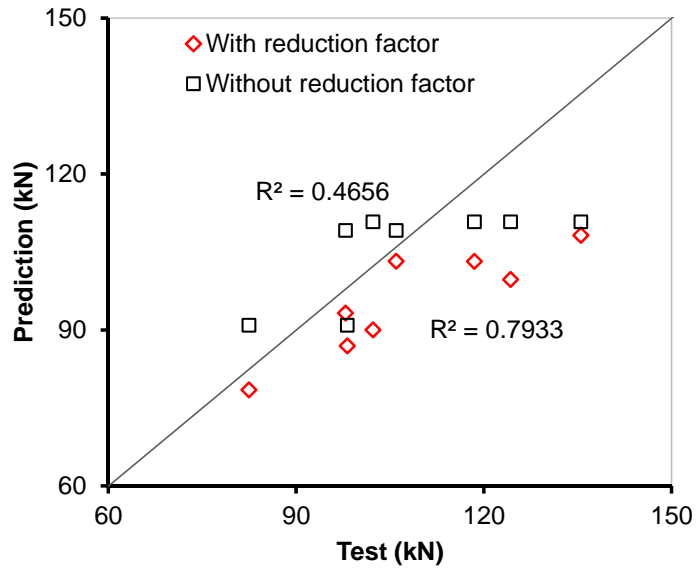


(b) side view

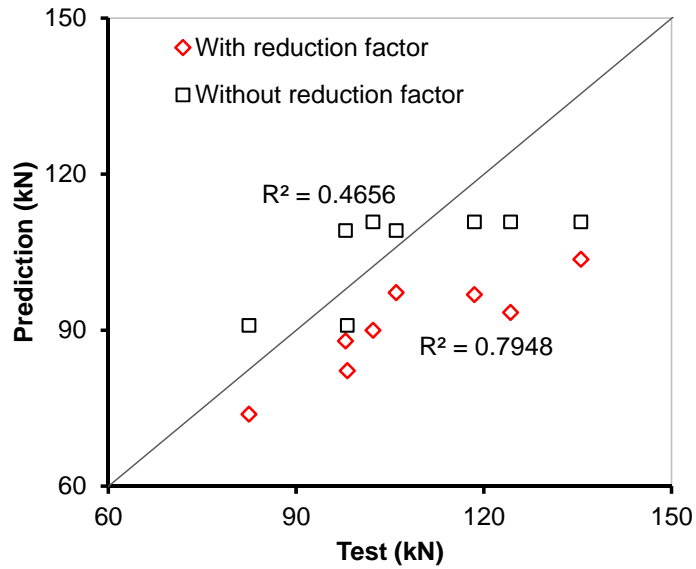


(c) front view

Figure 8. Test setup used by the authors



(a) Prediction using the accurate reduction factor (Eq. 5)



(b) Prediction using the simplified reduction factor (Eq. 6)

Figure 9. Comparison of bond strength between predictions and test results: (a) Prediction using the accurate reduction factor (Eq. 5); (b) Prediction using the simplified reduction factor (Eq. 6)