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Mechanical hinge system for delamination tests in beam-type composite specimens

N. Blanco^{a,*}, E.K. Gamstedt^b, J. Costa^c

^a*Advanced Materials and Analysis for Structural Design, Escola Politècnica Superior, University of Girona, Campus Montilivi s/n, E-17071 Girona, Spain*

^b*Department of Fibre and Polymer Technology, Royal Institute of Technology (KTH), Teknikringen 56-58, SE-100 44 Stockholm, Sweden*

^c*Advanced Materials and Analysis for Structural Design, Escola Politècnica Superior, University of Girona, Campus Montilivi s/n, E-17071 Girona, Spain*

Abstract

During the experimental study of composite delaminations external loads are usually applied by means of steel or aluminium parts bonded to the surface of beam-type specimens. The bonded joints between the metallic parts and the composite specimens might fail, especially when the tests are carried out under extreme temperatures or fatigue conditions. In addition, the point of application of the external load does not coincide with the neutral axis of the specimen beam, inducing non-linear effects that can lead, for example, to incorrect estimations of fracture toughness. In this paper, the relative importance of the non-linear effects in delamination tests is evaluated and the corresponding correction factors discussed. Next, the design of an improved mechanical hinge that avoids non-linear effects, eliminates bonded joints and can be adapted to different specimen thicknesses is introduced.

Key words: A. Polymer-matrix composites (PMCs), B. Delamination, B. Fracture toughness, A. Adhesive joints, Mechanical hinge.

23 1 Introduction

24 Beam-type specimens are widely used to experimentally study the static and
25 fatigue growth of composite delaminations under laboratory conditions, as well
26 as to determine the peel and shear resistance of adhesives. These specimens
27 are generally tested in mode I using the double cantilever beam test (DCB),
28 in mode II using the end-notched flexure test (ENF) or the end load split test
29 (ELS) and in mixed-mode I/II using the mixed-mode bending test (MMB) or
30 the mixed-mode end load split test (MMELS). Except for the ENF test, which
31 basically consists of a three-point bending test, the other tests mentioned need
32 a loading system to apply the force. Figure 1 shows a schema of the two systems
33 most commonly used: end blocks and piano hinges [1,2]. The figure also shows
34 the reduction of the lever arm when the loaded beam deflects under a load
35 applied with eccentricity.

36 The two loading systems, end blocks and piano hinges, have the advantage
37 of being conceptually very simple and easy to attach to the beams of the
38 specimen. However, their use can introduce non-linear effects during the tests
39 that can lead to error in the data reduction of the experimental results. An
40 additional disadvantage is that they must be adhesively bonded to the spec-
41 imen. Even though a surface treatment is applied before bonding, the bond
42 strength between the metallic part and the specimen can be low, especially for
43 thermoplastic-matrix composites, eventually resulting in a premature failure
44 of the joint (mainly in fatigue or high temperature tests). Moreover, misalign-

* Corresponding author. Tel.: +34 972418853; fax: +34 972418098.

Email addresses: `norbert.blanco@udg.edu` (N. Blanco), `gamstedt@kth.se`
(E.K. Gamstedt), `josep.costa@udg.edu` (J. Costa).

(a) End block loading system

(b) Piano hinge loading system

Fig. 2. Cross-section of the fastener box designed by Brandt [3] without and with the mounted specimen.

45 ments between the specimen and the load system can appear.

46 Brandt [3] introduced a mechanical hinge to overcome these problems. The
47 hinge consisted of two parts: the fastener box, which is mechanically attached
48 to the beam of the specimen, and the grip plate, which is mounted on the test
49 machine. The fastener box is a metallic block with a slot where the beam of
50 the specimen is fitted (the geometry of the specimen has to be modified, as
51 shown in Figure 2). Even though this hinge overcomes the problems associ-
52 ated with the use of end blocks and piano hinges (the rotation centre of the
53 hinge is very close to the neutral axis of the beam and no adhesive joints are
54 employed), it cannot be precisely adapted to different specimen thicknesses
55 and its manufacture is expensive.

56 In this work, an improved and easy to manufacture hinge has been designed for
57 delamination and adhesive tests using beam-type composite specimens. The
58 proposed design is mechanically fixed to the specimen to avoid premature fail-
59 ures due to poor bonding and can be easily aligned to the specimen. Moreover,
60 the hinge can be adapted to different specimens with different thicknesses and,
61 most importantly, it avoids non-linear effects.

62 The article starts with a brief quantitative study of the non-linear effects
63 induced by piano hinges and end blocks on common composite specimens for

64 different delamination tests. Then, the developed hinge is presented with a
65 thorough description of its mechanical design and performance.

66 **2 Non-linear effects in beam-type delamination specimens**

67 The use of end blocks or piano hinges during delamination and adhesive tests
68 generates a series of structural non-linear effects caused by the distance be-
69 tween the rotation centre of the loading system and the neutral axis of the
70 beam (distance l_1 in Figure 1). When the beam of the specimen deflects, the
71 lever arm between the load application point and the delamination front is
72 additionally reduced: a'' instead of a' in Figure 1(c). In addition, an end block
73 stiffens the end portion of the specimen, including part of the zone between
74 the load line and the delamination front (distance l_2 in Figure 1(a)).

75 To account for these effects, Williams [4,5] introduced two correcting factors, F
76 and N , in the calculation of the compliance ($C_{\text{corrected}} = \frac{C}{N}$) and energy release
77 rate ($G_{\text{corrected}} = G \frac{F}{N}$). F compensates for the reduction of the lever arm due
78 to the eccentricity of the loading system and the rotation of the specimen,
79 whereas N compensates for the stiffening of the specimen when end blocks
80 are used.

81 The correcting factor N will not be analyzed in this study because it is not
82 required when using piano hinges and, even with end blocks, the effect is
83 smaller than that of F . According to Williams [4,5] and Hashemi et al. [6–8],
84 the expression of F for the ELS, ENF and MMELS (mixed-mode end load
85 split) delamination tests is

$$F = 1 - \theta_1 \left(\frac{\delta}{L} \right)^2 - \theta_2 \left(\frac{l_1 \delta}{L^2} \right) \quad (1)$$

86 where the parameters θ_i were determined by Williams [4] and Hashemi et
87 al. [6–8]. To the knowledge of the authors, no specific expressions have been
88 formulated for the MMB test to determine these parameters. For the DCB
89 test, the length of the interlaminar crack a , must be used instead of the length
90 of the specimen, [1, 2, 4, 5, 9, 10].

91 It should be noted that the crack length a is required to determine the value
92 of the parameters θ_i ([4, 6–8]). However, the exact determination of a can be a
93 significant source of uncertainty due to the difficulties in locating the crack tip
94 (the crack front is not straight and the crack length measured on both edges
95 of the specimen is different). Due to this imprecision in the determination of
96 the crack length, the values of F and N can be imprecise.

97 In order to determine the importance of these non-linear effects, the influence
98 of F and its variation with the crack length is evaluated for the DCB, ELS
99 and MMELS delamination tests. The ENF test is not considered because a
100 different loading system has to be employed. For this purpose, the mechanical
101 properties of a typical unidirectional carbon/epoxy prepreg have been taken
102 into account (Table 1). The average thickness of the cured plies has been
103 taken as 0.125 mm. The specimen is considered to have 20 plies per beam
104 (total thickness is $2h = 5$ mm), the width is $b = 20$ mm and the effective
105 length is $L = 150$ mm. For practical reasons, the range of variation of the
106 crack length a is taken between 10 and 100 mm. All the plies are assumed to
107 be oriented with the fibres in the longitudinal direction of the specimen and
108 the interlaminar crack located in the midplane of the specimen.

Table 1

Mechanical properties of a typical unidirectional carbon/epoxy prepreg with a ply thickness of 0.125 mm (*critical energy release rate for a mixed-mode $G_{II}/G = 0.5$).

E_{11}	$E_{22} = E_{22}$	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$	G_{23}	G_{Ic}	$G_{I/IIc}^*$	G_{IIc}
(GPa)	(GPa)	–	–	(GPa)	(GPa)	(J/m ²)	(J/m ²)	(J/m ²)
125	10	0.3	0.5	5.5	3.5	250	500	1000

109 A similar analysis considering three different carbon-reinforced composites was
 110 previously conducted by Williams [4]. However, in this analysis Williams only
 111 considered the DCB specimen and did not take into account the value of δ
 112 required for crack propagation for every value of a (see [6] for further details).

113 The variation of F with the crack length for the DCB, ELS and MMELS
 114 tests for different values of l_1 is shown in Figure 3. In this figure, F has been
 115 calculated considering the displacement δ that corresponds to the critical value
 116 of the energy release rate of the material. Thus, for every value of a , the δ
 117 required for crack propagation is determined using G_{Ic} for the DCB test and
 118 G_{IIc} for the ELS test. In the case of the MMELS test, δ is calculated for every
 119 crack length according to the critical energy release rate of the material under
 120 mixed-mode I/II, $G_{I/IIc}$. Actually, for this test, the mixed-mode ratio G_{II}/G
 121 (mode II energy release rate over total energy release rate) varies from G_{II}/G
 122 = 0.335 when $a = 10$ mm to $G_{II}/G = 0.416$ when $a = 100$ mm (for further
 123 details see [11–13]).

124 According to Figure 3(a), the non-linear effects associated with F can be ne-
 125 glected in the case of the DCB test provided that the distance l_1 is sufficiently
 126 small (correction factor less than 5 % for the range of a and l_1 considered).

(a) DCB

(b) ELS

127 This is in good agreement with the maximum value of l_1 calculated according
128 to the ASTM standard for the DCB test [1] and the mechanical and geomet-
129 rical properties considered. In this case, $l_{1,\max} \approx 18$ mm.

130 In Figure 3(b), it can be observed that the influence of the correction factor
131 F is really important for the ELS test, especially for relatively short cracks.
132 In fact, when the distance l_1 is equal to 20 mm, the value of F can be as high
133 as 3.5. Unexpectedly, it may be observed that the correction factor does not
134 tend to unity for vanishing values of l_1 and short crack lengths, as it would
135 be expected. In a similar way, the influence of F for the MMELS test (Figure
136 3(c)) increases with increasing values of l_1 . For crack lengths shorter than 57.5
137 mm, the value of F is lower than 0.9. Actually, in the case of $l_1 = 20$ mm, F
138 becomes negative when a is shorter than about 11.5 mm, which lacks physical
139 meaning.

140 In summary, the non-linear effects for ELS and MMELS are relevant. Besides
141 that, the standard correction factor to account for these non-linear effects
142 exhibits physical inconsistencies in the explored range of a and l_1 . Furthermore,
143 the expressions of F and N to correct the non-linear errors generated during
144 the test can be imprecise due to the imprecision in determining the crack
145 length in delamination and adhesive tests. The problems of addressing these
146 significant non-negligible non-linear effects can be avoided altogether if the
147 proposed simplified hinge, where the load is applied at the neutral axis of the
148 beam, is used.

149 3 New hinge for delamination tests

150 The hinge designed in the present work, like the one proposed by Brandt [3],
151 is mechanically fastened to the specimen, thereby avoiding adhesive failures
152 during temperature or fatigue tests, reducing the distance between the load
153 application point and the neutral axis of the beam of the specimen and having
154 no stiffening effect. In addition, and in contrast to the solution introduced by
155 Brandt [3], the proposed design can be easily adapted to different specimens
156 with different thicknesses (assuring that the load application point coincides
157 with the neutral axis of the beam) and can be manufactured less expensively
158 and more easily.

159 The new hinge is composed of a fastener box and a grip. The fastener box
160 consists of two parts: a bottom case and a top case. The bottom case is made
161 of a metallic plate with a drilled zone where the beam of the specimen is
162 fitted. Five holes are drilled for the five fixing bolts to join the two parts of
163 the fastener box. A schema of the top case is shown in Figure 4(a) (where b
164 stands for the width of the specimen). The top case consists of a metallic plate
165 in which two holes have been drilled for the shafts of the grip. The specimen
166 beam is fitted between the two shafts in such a way that the neutral axis of
167 the beam coincides with the centre of the shafts. A schema of the bottom case
168 is shown in Figure 4(b).

169 When both parts of the fastener box, the bottom case and the top case, are
170 joined by the fixing screws, the beam of the specimen is clamped in between. In
171 this way, the hinge can be easily adapted to different specimen thicknesses. The
172 correct position of the shafts is ensured by modifying the distance between

(a) Top case (b) Bottom case (c) Grip

Fig. 4. Schema of the (a) top case, (b) bottom case and (c) grip of the designed load hinge.

173 the top and bottom plates inserting a metallic plate with the appropriate
174 thickness t between the top case and the specimen.

175 The grip is connected to the testing machine and carries the load to the
176 specimen through the fastener box. The design of the grip is very similar to
177 that proposed by Brandt [3] and is composed of two parts: the grip plate and
178 the grip arm. Both the grip plate and the grip arm have a pin at one extreme
179 to act as the rotation point for the fastener box and specimen. The grip arm
180 is connected to the grip plate by the two guiding pins while a locking bolt
181 secures the joint between both parts. A schema of the proposed grip is shown
182 in Figure 4(c).

183 The assembly of the designed hinge is shown in Figure 5(a). The metallic plate
184 with the appropriate thickness t and a generic specimen are also represented
185 in the figure. For reasons of simplicity, an ELS or MMELS specimen is repre-
186 sented, so only one beam of the specimen has to be loaded. Fitting between
187 the bottom case and the specimen is achieved by cutting the extreme part of
188 the unloaded beam, as shown in the figure.

189 In the case of the ELS or MMELS delamination tests, the designed hinge

(a) Assem- (b) Designed
 bly of the load hinge dur-
 hinge and the ing a MMELS
 specimen test

Fig. 5. (a) View of the assembly of the hinge and the specimen (an ELS or MMELS delamination specimen is considered for simplicity) and (b) designed load hinge during a MMELS test where the load application point is centred at the neutral axis of the beam.

190 does not require a special specimen lamination process. The specimens can
 191 be laminated in the usual way and fitting them into the hinge only requires
 192 cutting the extreme end of the unloaded beam, as shown in Figure 5(a). In
 193 fact, the proposed hinge was used by the authors in different MMELS fatigue
 194 delamination tests under varying mode mix conditions at room temperature
 195 [11,12]. In total, the hinge supported more than 20 million cycles without any
 196 slippage between it and the specimen or any other functional problem. Two
 197 different specimens with different thicknesses in the loaded beam, 0.65 and
 198 2.6 mm, were employed for the tests. The hinge could be easily adapted to
 199 each specimen thickness by using two metallic plates of different thicknesses
 200 so that correct alignment between the load application point and the neutral
 201 axis was obtained. Figure 5(b) shows the hinge used during the MMELS tests
 202 and how the external load is applied to the neutral axis of the loaded beam
 203 of the specimen.

204 The adaptation of the designed hinge to the DCB and MMB tests can be

205 problematic, as in the case of using the hinge designed by Brandt. Two bottom
206 cases have to be fixed to the specimen and two top cases and grips must be
207 employed. The first problem appears when the two bottom cases are fixed in
208 the delamination plane between the beams of the specimen without excessively
209 opening the interlaminar crack. The second problem in adapting this type of
210 hinge to DCB or MMB tests is the interference between two sets of top cases
211 and grips.

212 There are three alternatives to adapting the designed hinge to the DCB or
213 MMB test and to overcoming the problem of fixing two bottom cases to the
214 specimen. The first possibility is to machine the specimens or use a specific
215 process for their manufacturing in order to obtain a geometry similar to the
216 one proposed by Brandt (see Figure 2 and [3] for details). A second possibility
217 is to carefully force two bottom cases between the beams of the specimen and
218 then fix them to two upper cases. The advantage of this alternative is that
219 the geometry of the specimen does not have to be modified as in the previous
220 case. The disadvantage of this method is that an initial displacement of the
221 beams is introduced and forces an initial opening, without measured load,
222 of the interlaminar crack. This alternative has been used by the authors in
223 different static DCB and MMB tests for the characterisation of interlaminar
224 crack resistance of carbon fibre-reinforced polymer laminates with very good
225 results and values of G similar to those obtained with piano hinges [14, 15].
226 The third option for adapting the designed hinge to the DCB and MMB tests
227 is based on the use of the usual specimen geometry but only the top cases of
228 the proposed hinge are bonded at each beam of the specimen. Although this
229 alternative includes the disadvantage of an adhesive joint between specimen
230 and hinge, the load is still applied to the neutral axis of the beam. Nonetheless,

231 to avoid any interference between the two sets of top cases and the grips
232 when using the hinge for the DCB or MMB test, one of the sets has to be
233 manufactured with an increased distance between the shaft holes and shafts
234 of the top case and the grip, respectively (see Figures 4(a) and 4(c)). The
235 increased distance must be sufficient to avoid interference when superposing
236 the two top cases and grips.

237 The designed hinge has been used by the authors in a multitude of different
238 static and fatigue delamination tests, including DCB, MMB and MMELS
239 tests, involving beam-type specimens with different thicknesses [11,12,14,15].
240 In all cases, the loading point of the hinge and the neutral axis of the beam were
241 coincident. In total, the hinge has been used for more than 20 million loading
242 cycles at different load-displacement levels without any problem, especially
243 those related to end blocks and piano hinges.

244 4 Conclusions

245 A design for an improved and simplified hinge for composite delamination
246 and adhesive tests using beam-type specimens has been presented. The pro-
247 posed solution does not include adhesive joints susceptible to failure during
248 the tests, especially under fatigue or severe environmental conditions, as in
249 the case of the commonly used piano hinges and end blocks. Moreover, the
250 proposed design ensures that the applied force is centred at the neutral axis
251 of the beam, independently of the thickness of the specimen. Thus, the non-
252 linear effects generated when the point of application of the external load and
253 neutral axis of the beam do not coincide are avoided. It has been also shown
254 that for certain delamination tests these non-linear effects are important and

255 cannot be neglected, requiring the use of different correction factors (which
256 in turn exhibit some inconsistencies for short crack lengths). Consequently,
257 the hinge presented in this work allows calculation of the energy release rate
258 components without taking into account correcting factors that complicate
259 the calculations.

260 The hinge is manufactured with top and bottom cases. A metallic plate can
261 be inserted between the top case and the specimen, so the hinge can fit a
262 wide range of specimen thicknesses while keeping the load application point
263 centred at the neutral axis of the beam. Some indications on how to adapt the
264 proposed hinge for DCB and MMB delamination and adhesive tests, in which
265 two sets of hinges are required, have been given.

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271 MAT2006-14159-C02-01.

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Figure 1a

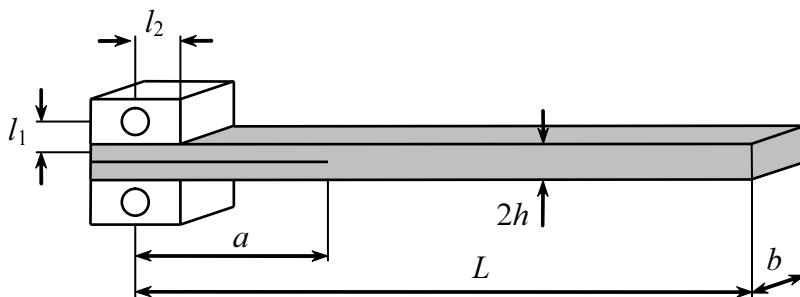


Figure 1b

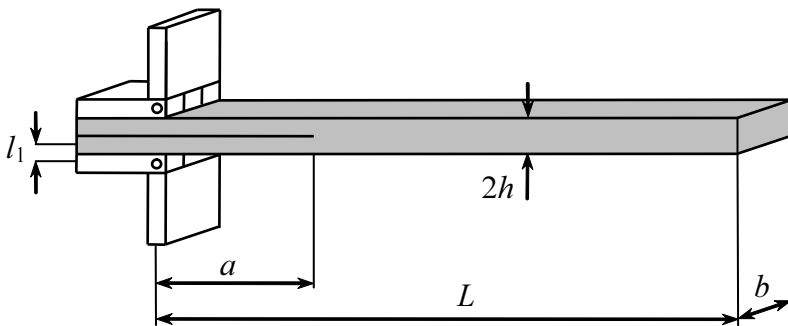


Figure 1c

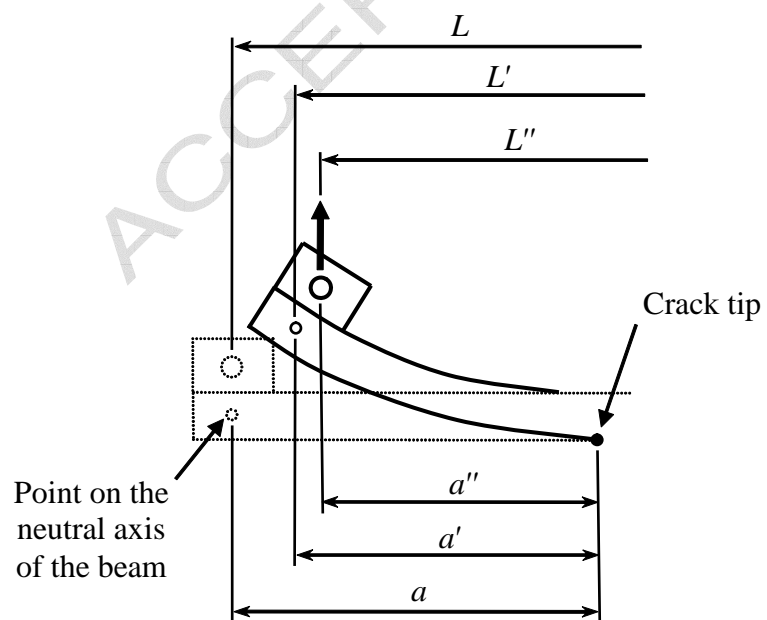


Figure 2

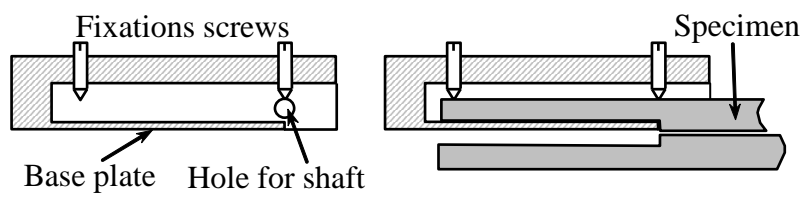


Figure 3a

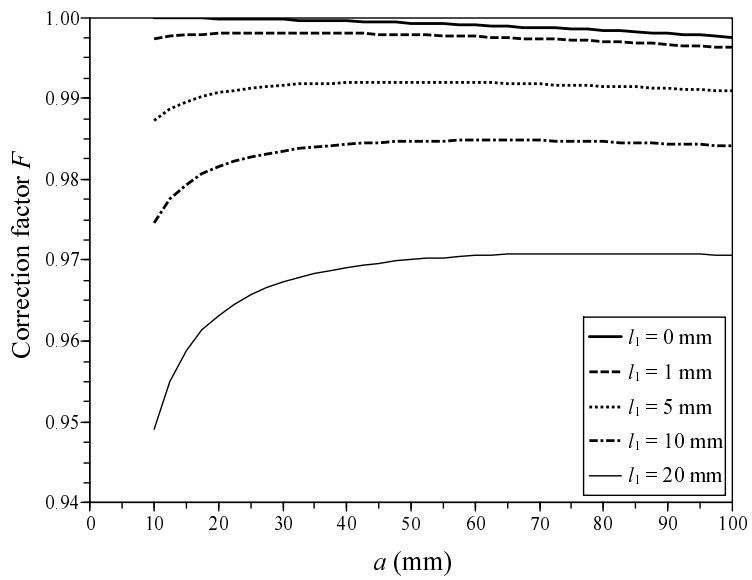


Figure 3b

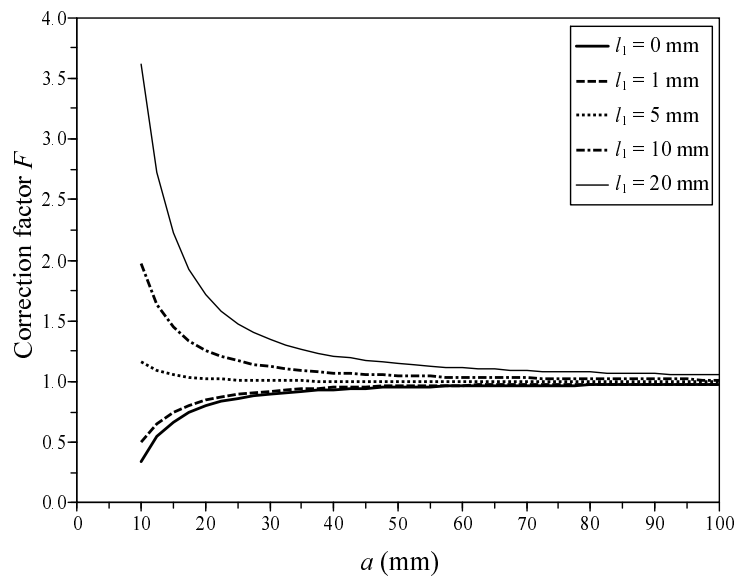


Figure 3c

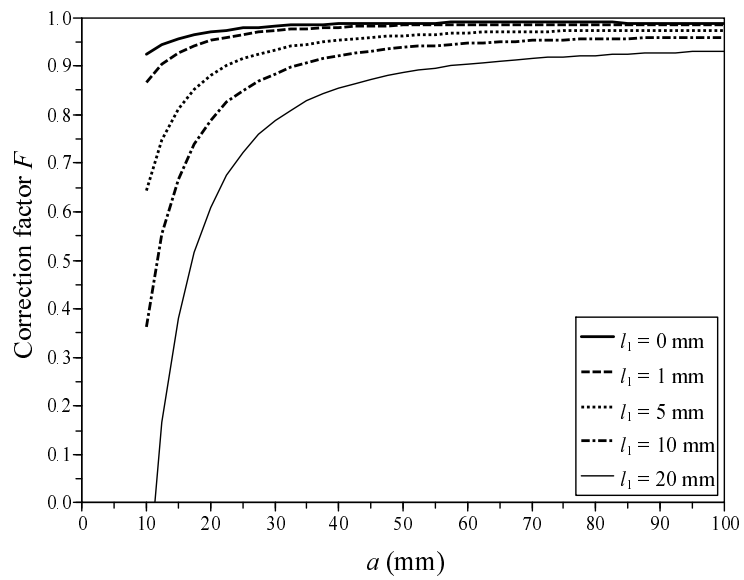


Figure 4a

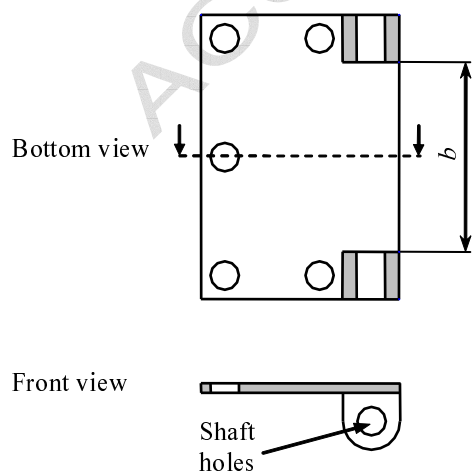


Figure 4b

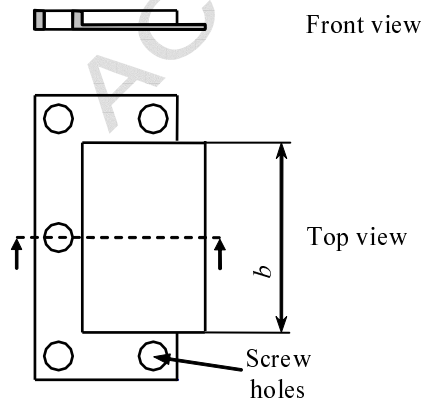


Figure 4c

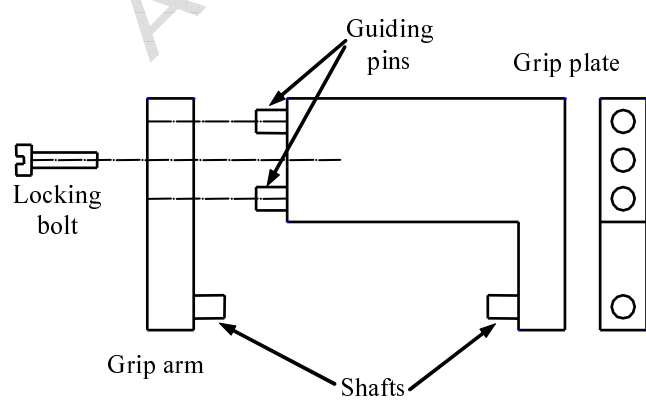


Figure 5a

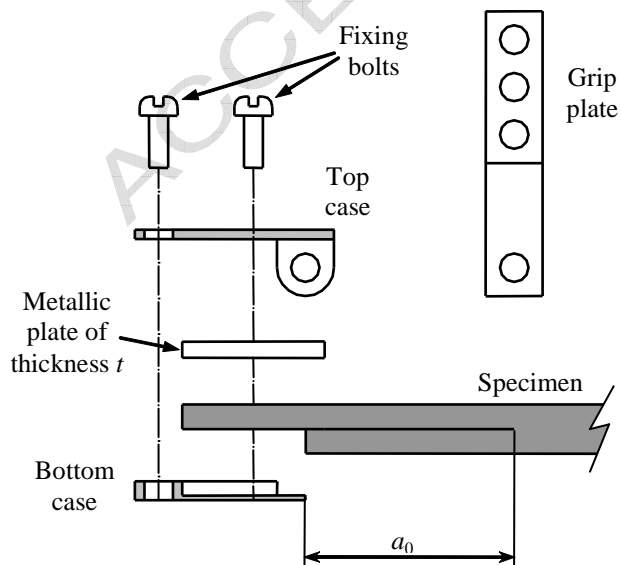


Figure 5b

