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# Accepted Manuscript

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1 **Deformation of Thin Plates Subjected to Impulsive Load: Part III – An Update 25 years**

2 **on**

3 S. Chung Kim Yuen, G. N. Nurick, G. S. Langdon and Y. Iyer

4

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8

9 **Highlights**

- 10 • Air blast experiments on flat steel plates
- 11 • Review of 25 years of blast experimentation
- 12 • Update of dimensionless analysis
- 13 • Check to see that post 1989 test data correlates with dimensionless analysis
- 14 approaches

15 **Abstract**

16 In 1989, Nurick and Martin published two review papers on the deformation of thin steel

17 plates subjected to impulsive air-blast loading. The state of the art has progressed

18 significantly in the following 25 years, and this review paper restricts itself to experimental

19 studies that investigate the response of monolithic metal plates subjected to air-blast loading

20 generated by detonating plastic explosive. From the large numbers of experiments reported, it

21 is shown that the failure progressions in circular and quadrangular plates are similar and can

22 be adequately described by three “failure modes” – namely large plastic deformation (mode

23 I), tensile tearing (mode II) and shearing (mode III) although the severity and location of

24 these failures on the plates is primarily determined by spatial distribution of the blast loading

25 across the plate surface, and that boundary conditions significantly influence the onset of

26 shearing and tearing failures due to variation in the in-plane movement of the plate material.

27 The non-dimensional analysis approaches used by Nurick and Martin have been expanded to  
28 include the effects of load localisation and stand-off distance, and show good correlation with  
29 the expanded sets of test data published since 1989. It is concluded that these approaches still  
30 hold merit as simple tools for evaluating the likely effect of a close proximity air blast load  
31 on a flat metal plate.

## 32 **Keywords**

33 *Blast loading, plates, failure modes, deformation, non-dimensional analysis*

34

## 35 **Notation**

36  $B$  plate width

37  $I$  impulse

38  $L$  plate length

39  $R$  exposed plate radius

40  $R_o$  charge radius

41  $S$  stand-off distance

42  $t$  plate thickness

43  $W$  TNT equivalent mass

44  $Z$  Hopkinson scaled distance

45  $\delta$  permanent mid-point displacement

46  $\phi_c$  non-dimensional impulse for circular plates

47  $\phi_{cS}$  non-dimensional impulse for circular plates, incorporating stand-off distance

48  $\phi_q$  non-dimensional impulse for quadrangular plates

49  $\rho$  material density

50  $\sigma$  characteristic stress = quasi-static yield stress

51

## 52 **1. Introduction**

53 The study of structural response to impulsive blast loading has been performed for many  
54 years. In 1989, Nurick and Martin[1, 2] reviewed data from previous experimental and  
55 theoretical investigations into the response of flat, monolithic metal plates subjected to blast  
56 loading. In addition, new experimental data was reported and non-dimensional analysis was  
57 utilised with the aim of developing a simple, empirical prediction of the displacement of a  
58 blast loaded plate with fully clamped boundary condition[2]. Since 1989, there have been  
59 many experimental, analytical and numerical modelling investigations into the response of  
60 structures to blast loading. These have expanded the types of structures examined to include  
61 different plate geometries, stiffened and welded structures, sandwich panels, composite  
62 materials and monolithic metal plates with different boundary conditions. Tensile tearing and  
63 shear failures have also been investigated alongside large plastic deformation responses.  
64 Different forms of loading, including localised loading and stand-off distance effects have  
65 also been studied.

66  
67 This paper reviews the literature that has published since 1989 in an attempt to update the  
68 work presented by Nurick and Martin[1, 2]. Using the post 1989 developments in non-  
69 dimensional analysis, much of the more recent experimental data is then translated into non-  
70 dimensional impulse and displacement parameters and plotted alongside the data presented in  
71 ref[2] to determine if the empirical relationships proposed in 1989 are still valid. Due to the  
72 myriad of papers in this area, this review paper restricts itself to experimental studies that  
73 investigate the response of monolithic metal plates subjected to air-blast loading generated by  
74 detonating plastic explosive. Unless otherwise stated, the reviewed results are concerned with  
75 flat mild steel plates.

76

## 77 2. Experimental studies since 1989

78 In order to summarise the experimental work performed in the past twenty five years, the  
79 studies presented in the literature are summarised in Table 1 according to the following  
80 classifications:

- 81 • Loading type: uniform, localised, varying stand-off distance,
- 82 • Plate geometry: circular or quadrangular; stiffened or flat,
- 83 • Boundary conditions, and
- 84 • Failure mode: large plastic deformation, tensile tearing, shear failure.

85

### 86 2.1 Uniform loading conditions

87 Teeling-Smith and Nurick[3] investigated the progression in failure of clamped circular  
88 plates subjected to uniform blast loading. Photographs of plate failures at different impulses  
89 are shown in Figure 1. At low impulse levels, large plastic deformation (known as Mode I  
90 failure) was observed, with mid-point displacement increasing with increasing impulse. As  
91 impulse was increased, thinning occurred at the plate boundary (known as Mode Ia or Mode  
92 Ib, depending upon the proportion of the circumference that exhibited necking) which was a  
93 precursor to tensile tearing along the boundary edge[3]. As impulse reached a threshold  
94 value, partial tearing (known as Mode II\*) of the plate edge occurred. This Mode II\* failure  
95 is the transition between Mode I and Mode II (tensile tearing of the boundary edge) failure.  
96 As impulse increased further, plates exhibited tensile tearing of the boundary edge. If the  
97 impulse was increased beyond the threshold required for complete boundary tearing, the mid-  
98 point displacement of the plates decreased with increasing impulse and the failure mode  
99 tended towards transverse boundary shear (known as Mode III)[3]. The observed failure  
100 modes were similar to those reported by Menkes and Opat[4] for explosively loaded beams  
101 and the definitions of the failure modes are summarised in Table 2 for blast-loaded plates.

102

103 Nurick and co-workers[5, 6] investigated the influence of boundary conditions on the failure  
104 of uniformly loaded circular plates in follow-on studies from the work reported in ref[3].  
105 Thomas and Nurick[5] compared the fully clamped and built-in boundary conditions and  
106 showed that the boundary condition has little influence upon plate response during Mode I  
107 (large plastic deformation) failures. However, the onset of boundary thinning and  
108 subsequently boundary tearing were significantly influenced by the type of boundary  
109 condition. The built-in plates exhibited the onset of thinning and tearing at lower impulses  
110 since the boundary was more rigid and the clamped boundary was unable to fully prevent in-  
111 plane movement of the plate[5]. There was also a difference in the curvature of the plates at  
112 the boundary – the clamped plates exhibited curvature within the clamped region whereas the  
113 built-in plate curvatures began at the built-in edge[5]. Nurick et al.[6] investigated the effect  
114 of a sharp or filleted edge on the response of fully clamped circular plates. The filleted edge  
115 clamps delayed the onset of thinning and tearing failures to higher plate displacements,  
116 whereas the sharp edged clamp failed at the lowest impulse levels. The sharp edge caused an  
117 indentation in the plate which initiates necking[6]. Plates with curved edges exhibited  
118 necking without any indentations, similar to that observed during tensile test[6].

119

120 Cloete et al.[7] reported results from tests involving uniformly loaded clamped circular  
121 plates. In addition to the boundary clamping, the plates either had a centrally located hole  
122 (referred to as annular) or were prevented from deforming with a central support. The central  
123 support was a Hopkinson bar, enabling transient force measurements to be taken during the  
124 structural response phase. During the annular plate tests, the duration of the blast load was  
125 typically in the order of 50 ms and showed the classical blast wave characteristics of a sudden  
126 rise followed by an exponential decay. Three distinct modes of failure for fully clamped

127 circular plates were observed from the tests on plates with a central support. The failure mode  
128 definitions were similar but not identical to those reported for circular plates[3]. A distinction  
129 was made between tensile and shear failures that occur prior to and subsequent to large  
130 plastic deformation, something which was only possible due to the transient measurements  
131 from the Hopkinson bar. The maximum transverse shear stress that the plates could sustain  
132 along the inner boundary was relatively consistent and marked the transition from failure  
133 subsequent to large deformation and failure prior to large deformation[7].

134

135 Olson et al.[8] and Nurick and Shave[9] investigated the progression in failure of clamped  
136 quadrangular plates subjected to uniform blast loading. Photographs of plate failures reported  
137 in ref[9] are shown in Figure 2. Similar failures modes were observed for quadrangular plates  
138 as for circular plates, when the work in refs[8, 9] is compared to the work of Teeling-Smith  
139 and Nurick[3]. At low impulse levels, large plastic deformation was again observed, with  
140 mid-point displacement increasing with increasing impulse. As impulse was increased,  
141 thinning occurred at the centre of the plate boundary which progressed to tearing failure with  
142 further increases in impulse[8, 9]. The tensile tearing also initiated at the centre of one of the  
143 boundary edges and progressed towards the corners at higher impulses[8]. In-plane  
144 movement (often referred to as “pulling-in”) was observed as displacement increased and  
145 tearing occurred[8]. If the impulse was increased beyond that required for complete boundary  
146 tearing, the mid-point displacement of the plates decreased with increasing impulse and the  
147 failure mode tended towards transverse boundary shear (known as Mode III).

148

149 Bonorchis and Nurick[10] extended the work on boundary conditions reported in refs [5, 6]  
150 to study the influence of boundary conditions on the response of quadrangular plates  
151 subjected to uniform loading. Plates with clamped, built-in and welded (both TIG and MIG)

152 boundaries were tested under the same loading conditions. Similarly to the results obtained  
153 by Thomas and Nurick[5] for circular plates, large plastic deformation response was  
154 unaffected by boundary condition, but the initiation of tensile failure was significantly  
155 influenced by the imposed boundary condition. The impulse required for boundary tearing  
156 was lowest for the built-in plates and next lowest for the welded plates. The clamped plates  
157 required the highest impulse to initiate tearing, again due to the in-plane movement of the  
158 clamped plates.

159

160

## 161 ***2.2 Localised blast loading***

162 Nurick and co-workers[11, 12] reported results from localised blast tests on fully clamped  
163 circular plates. The loading was generated by detonating centrally located disks of plastic  
164 explosive (PE4) in close proximity to the plates. The dimensions of the PE4 disk (diameter  
165 and charge height) were varied, along with charge mass, to produce a range of responses in  
166 the plates from low levels of plastic deformation through to tearing of the plates in the central  
167 region. Photographs of failed plates are shown in Figures 3 and 4[13]. The localisation of the  
168 loading caused a change in plate profile when compared to uniformly loaded plates. Instead  
169 of a single dome, the locally loaded plates exhibited a global dome with a secondary inner  
170 dome superimposed on top in the central region. The inner dome diameter increased with  
171 increased charge diameter, as might be expected. At higher impulses, thinning and tearing  
172 occurred in the central region, followed by capping failure. After capping, the remaining plate  
173 has a centrally located hole, the diameter of which is also proportional to the charge diameter.  
174 As impulse increased beyond that required for capping, radial cracks propagated in the plate  
175 away from the central cap and caused petalling failure.

176

177 Yuen and Nurick[13] investigated the effects of load-plate diameter ratio and plate thickness  
178 on the response of locally blast-loaded circular plates with built-in boundaries. In many tests,  
179 the same capping failures observed in refs[11, 12] were observed, but it was also shown that  
180 thicker plates with small load diameters exhibited petalling failures rather than capping  
181 failure. Once the load-plate diameter was greater than or equal to 0.4, the loading was less  
182 localised and tearing failure occurred at the plate boundary rather than in the central region.

183

184 Jacob et al.[14] reported a study on the influence of plate and load geometry on the response  
185 of clamped quadrangular plates subjected to localised blast loading. Plate thickness was  
186 varied from 1.6 mm to 4 mm. The plate aspect ratio was varied from 1:1 (square) to 2.4:1  
187 (rectangular). Various charge diameters and charge masses were used. It was found, that over  
188 the whole range of plate thicknesses, charge diameters and aspect ratios, the response of the  
189 quadrangular plates was similar in form to that of circular plates[14]. Photographs of some  
190 typical plate profiles are shown in Figure 5, where the inner dome atop a global dome is again  
191 observed for Mode I failure (followed by capping failure at higher impulses) as it was for  
192 circular plates in refs[11-13]. Similar results were reported by Langdon et al.[15] for built-in  
193 square plates subjected to localised blast loads.

194

### 195 *2.3 Plates subjected to blast loading at different stand-off distances*

196 Jacob et al.[16] performed an experimental investigation into the influence of stand-off  
197 distance on the response of clamped circular plates. The blast loading was generated by  
198 detonating small disks of PE4 at the open end of a tube. The tube directed the blast loading  
199 towards the clamped target plate. The plate had a diameter of 106 mm and a thickness of 1.6  
200 mm. Various tube lengths were used to provide stand-off distances ranging from 25 to 300  
201 mm. Large plastic deformation occurred in most of the experiments. At low stand-off

202 distances (up to 40 mm), the plate response was typical of those observed for locally loaded  
203 plates refs [11-13]. At large stand-off distances (above 100 mm), the plate response was  
204 typical of uniformly loaded plates, with stand-off distances between 40 and 100 mm, being  
205 described as a transition between the two loading regimes. Increasing stand-off distance  
206 therefore decreases load localisation. Jacob et al.[16] concluded that loading could be  
207 considered to be uniform when the stand-off distance exceeded the largest plate dimension

208

209 Neuberger et al.[17, 18] performed scaled experiments where the blast loading was  
210 generated by detonating spherical TNT charges (varying mass from 0.468 kg to 8.75 kg) at  
211 different stand-off distances (65 mm to 200 mm). The clamped circular test plates had  
212 diameters of either 0.5 m or 1 m and were manufactured from RHA steel. The main foci of  
213 the investigations were the achievement of geometrically similar scaling during the blast  
214 tests[17] and the influence of spring-back on response[18]. Neuberger et al. [17, 18]  
215 observed large plastic deformation of the plates that was similar to that observed by Jacob et  
216 al. [16].

217

218 Jacinto et al.[19] reported results from large scale experiments on quadrangular plates. The  
219 loading was generated by detonating charges with equivalent TNT masses varying from 0.8  
220 kg to 10 kg at stand-off distances of 30 m and 60 m. Two sets of plates were tested – one with  
221 dimensions 1.5 m by 1m by 2 mm (with three free edges and one edge clamped in a concrete  
222 base) and one with dimensions 0.95 m by 0.95 m by 0.9 mm (clamped in a frame on all four  
223 sides). Due to the large stand-off distance relative to the plate size, the loading was assumed  
224 to be uniformly distributed. Pressure transducers recorded transient pressure histories that  
225 were typical of far field loading, as shown in Figure 6. Most of the paper was focussed upon  
226 numerical modelling. Jacinto et al.[19] commented that the plates clamped in frames showed

227 greater vibrational damping than the plates with one edge clamped in a concrete base. This  
228 observation reinforces the findings reported by Nurick et al.[5, 6, 10, 20] on the importance  
229 of boundary conditions.

230

231 Large scale field tests involving the detonation of up to 26300 kg of ordnance per test were  
232 reported by Yuen et al.[21, 22]. Square plates (exposed area of 0.5 by 0.5 m) were clamped in  
233 test frames and situated at various stand-off distances from the explosive detonation site. The  
234 ordnance was laid out on the ground in carpet-like form (rather than the typical cylindrical or  
235 spherical shaped charges used in laboratories). The location of the charge on the ground,  
236 unusual explosive layout and casing of the explosive due to the ordnance types led to  
237 complex loading conditions (with ground effects, geometry effects and fragmentation damage  
238 respectively). Despite the complex loading, the resulting deformation was similar to that  
239 observed in lab-scale tests involving uniformly loaded clamped square plates[8, 9]. At the  
240 closer stand-off distances the ordnance casings became projectiles as a result of the  
241 explosions and perforated some of the plates. The perforation damage, however, seemed to  
242 have little influence on the global response of the panels. Hopkinson-Cranz scaling was used  
243 (and modified) to evaluate the loading parameters and allow empirical predictions of mid-  
244 point displacement. The empirical predictions gave reasonable agreement with the  
245 experimental results.

246

#### 247 *2.4 Stiffened plates*

248 Investigations into the response of stiffened plates to blast loading have mainly focussed on  
249 uniformly distributed loading[23-35]. As might have been anticipated, the addition of  
250 stiffeners, whether they are clamped into position[29, 31], welded[32], integral with the  
251 plate[30, 33], or riveted[34, 35] resulted in lower global displacements for a given impulse.

252 Schleyer et al.[32] showed that the direction of loading and the amount of in-plane restraint  
253 influenced the response of stiffened plates subjected to pulse pressure loading. Loading the  
254 plates such that the stiffeners were in tension resulted in slightly increased mid-point  
255 displacement compared with loading the plates with the stiffeners in compression. Plates with  
256 no in-plane restraint exhibited displacements that were much larger than those with in-plane  
257 restraint along the boundary edges[32]. The addition of stiffeners to the unrestrained plates  
258 had no discernable effect upon displacement[32]. The geometry, number and position of the  
259 stiffeners are of importance in the response of clamped plates. Yuen and Nurick[33] showed  
260 that uniformly loaded plates with more stiffeners are more effective at reducing permanent  
261 displacements, and that locating the stiffener along the mid-lines of the plates is more  
262 effective at reducing displacements than placing stiffeners at other positions. Stiffeners were  
263 shown to reduce the plate deformations but this led to the initiation of tearing failures at  
264 lower impulses when compared to unstiffened flat plate responses[33]. Tearing initiated  
265 along the plate boundary, usually along the side parallel to the stiffeners.

266

267 Localised loading of the same stiffened plates used by Yuen and Nurick[33] was reported by  
268 Langdon et al.[15]. A general failure progression of the stiffened plates emerged from the  
269 experimental results[15]: localised central dome, limited by the stiffener geometry; thinning  
270 along the stiffener-plate edges; tearing away from the stiffener edge and towards the  
271 boundary; petalling and in one case, stiffener rupture. The locations of tearing were strongly  
272 dependent upon the stiffener location[15], as shown in the photographs in Figure 7.

273

274 **3. Non-dimensional analysis**

275 Non-dimensional analysis can be used to compare the results from experiments performed on  
 276 panels of different scale, different material properties and tested under different loading  
 277 conditions.

278

279

280

### 281 *3.1 Circular plates*

282 In 1989, Nurick and Martin[1, 2] derived an expression, shown in Eq. (1) for circular plates,  
 283 that provided a non-dimensional impulse parameter for comparing blast-loaded panels of  
 284 different geometries (exposed radii and thicknesses) and different materials (densities and  
 285 characteristic stresses), to be treated similarly. The expression for non-dimensional impulse  
 286 given in Eq. (1) was then modified by Nurick and Martin[2] for localised blast loading of  
 287 circular plates as shown in Eq. (2). The experimental studies conducted since 1989 have  
 288 provided additional insight into the behaviour of plates under different loading conditions and  
 289 greater understanding of the factors affecting plate performance. In parallel with the  
 290 experimental studies reported above, Nurick and co-workers[14, 16] have further developed  
 291 the non-dimensional analysis of blast loaded plates to account for some of these additional  
 292 loading conditions.

293

$$294 \quad \emptyset_c = \frac{I}{\pi R t^2 (\sigma \rho)^{0.5}} \quad (1)$$

295 Where  $R$  = exposed plate radius,  $t$  = plate thickness,  $I$  = impulse,  $\rho$  = material density,  $\sigma$  =  
 296 characteristic material stress (quasi-static yield stress for monolithic metals) and  $\emptyset_c$  is known  
 297 as the non-dimensional impulse parameter for circular plates.

298

$$299 \quad \emptyset_c = \frac{I \left( 1 + \ln \left( \frac{R}{R_0} \right) \right)}{\pi R t^2 (\sigma \rho)^{0.5}} \quad (2)$$

300 Where  $R_0$  = load radius of a centrally located disc of explosive.

301

302 A modification to account for stand-off distance in the response of circular plates was  
 303 proposed by Jacob *et al.*[16], shown in Eq. (3), based upon tests conducted over a range of  
 304 stand-off distances (from 13 to 300 mm) where the blast was directed along a tube towards a  
 305 106 mm diameter metal target plate, as described previously.

$$306 \quad \phi_{cs} = \frac{I(1+\ln(R/R_0))}{(1+\ln(S/R_0))\pi R t^2 (\sigma \rho)^{0.5}} \quad (3)$$

307

308 Where  $S$  = stand off distance (SOD) between charge surface and target plate surface.

309

310 Nurick and Martin[2] found an empirical relationship between permanent deflection-  
 311 thickness ratio and non-dimensional impulse using data from over 100 tests. This  
 312 relationship, expressing in Eq. (4), is used for large inelastic displacement only, and not for  
 313 failures involving tensile tearing of the plate (capping in the plate centre or tearing at the  
 314 boundary) or shear failure (either in the central region or boundary of the plate).

315

$$316 \quad \frac{\delta}{t} = 0.425\phi_{cs} + 0.277 \quad (4)$$

317 Where  $\delta$  = permanent midpoint deflection of the plate.

318

319 The empirical relationship in Eq. (4) was determined from the slope of the non-dimensional  
 320 displacement versus non-dimensional impulse curve and had a correlation coefficient of  
 321 0.974. Since 1990, hundreds of additional tests have been performed on circular plates  
 322 subjected to various loading conditions. Data from these tests is combined with data obtained  
 323 prior to 1990 and is plotted in Figure 8 in terms of non-dimensional impulse and non-  
 324 dimensional displacement. The pre-1990 data went up to a non-dimensional impulse value of

325 approximately 25; 140 of the new data-points are in the range where non-dimensional  
 326 impulse is between 25 and 50. In total, 699 data-points are plotted in Figure 8, along with a  
 327 line described by Eq. (4) and a new regression line, given by the expression in Eq. (5). A  
 328 correlation coefficient of 0.928 is obtained for Eq. (5). As indicated in Table 3, 74% of the  
 329 data is predicted within a plate thickness and 90% of the data within 2 plate thicknesses of the  
 330 expression in Eq. (5). There is little difference between the new empirical expression in Eq.  
 331 (5) and the 1989 proposal[2], validating the original prediction in Eq. (4).

332

$$333 \quad \frac{\delta}{t} = 0.427\phi_{cs} + 0.298 \quad (5)$$

334

335 From an inspection of Table 3 and Figure 8, it is evident that the additional data agrees  
 336 particularly well with the data prior to 1990 for non-dimensional impulses below 25. Above a  
 337 non-dimensional impulse of 25, there is an upward trend in the displacement data away from  
 338 the lines described by Eqs (4) or (5). At higher non-dimensional impulses, thinning or  
 339 necking of the plates is likely to be occurring at the boundary, reducing the levels of in-plane  
 340 restraint and hence increasing the displacement exhibited by those plates as also observed by  
 341 Nurick and Teeling-Smith[36] for the range of deflection-thickness ratio higher than 10.

342

343 It should be noted that the empirical equations presented herein are restricted to mostly mild  
 344 steel plates which are known to be highly strain rate sensitive. There are a few data points on  
 345 aluminium plates. The slight variation in the various figures could be related, partly, to the  
 346 different strain rate sensitive properties of the various mild steels. Jones[37] showed how  
 347 strain rate effects can be considered for plating under explosive loadings. Yao et al.[38] very  
 348 recently presented some experimental results on locally blast loaded mild steel plates that were very  
 349 similar to those presented by Nurick and co-workers[14, 16]. Yao et al. [38] showed that there was a  
 350 linear trend of increasing displacement-thickness ratio with increasing dimensionless damage number  
 351  $D_{ex}$ , where  $D_{ex}$  used the Hopkinson scaled distance (shown in Eq. (6)) instead of impulse ( $I$ ) as the

352 loading parameter in the dimensionless analysis. This is similar to the approach taken by Yuen et  
 353 al.[22] for large scale explosions outdoors which employed empirical formulae to estimate the  
 354 impulse using the peak over-pressure and duration calculations from the Hopkinson scaled distance.  
 355 However, the stand-off distance range was small (12.9-17.6 mm) and the effects of the charge  
 356 geometry and plate stiffness were not considered. Hence, this work uses impulse with the appropriate  
 357 correction factors for stand-off distance, charge shape and plate geometry shown in Eq. (3).

$$358 \quad Z = \frac{S}{W^{1/3}} \quad (6)$$

359 Where  $Z$  = Hopkinson scaled distance and  $W$  = equivalent TNT mass of charge

360

### 361 *3.2 Quadrangular plates*

362 A similar approach to non-dimensional analysis has been followed for quadrangular plates.  
 363 The non-dimensional impulse  $\phi_q$  (or damage number) for quadrangular plates proposed by  
 364 Nurick and Martin[2] in 1989 is given in Eq. (7). This was modified by Jacob et al.[14] to  
 365 incorporate a loading parameter for localised loading, as shown in Eq. (8).

$$366 \quad \phi_q = \frac{I}{2t^2 (BL \rho \sigma)^{1/2}} \quad (7)$$

367

368 Where  $B$  = plate breadth;  $L$  = plate length

369

$$370 \quad \phi_{ql} = \frac{I \left( 1 + \ln \left( \frac{LB}{\pi R_0^2} \right) \right)}{2t^2 (LB \rho \sigma)^{1/2}} \quad (8)$$

371

372 In 1989, Nurick and Martin[2] plotted the deflection-thickness ratios obtained from uniform  
 373 loading tests against the non-dimensional impulse parameter given in Eq. (7). A regression  
 374 analysis was performed to obtain a line of best fit. The equation of the best fit line was  
 375 proposed as an empirical prediction for the large deformation response of blast-loaded

376 quadrangular plates and is shown in Eq. (9). A probability of 90% is obtained to predict mid-  
 377 point deflection within a plate thickness.

378

$$379 \quad \left( \frac{\delta}{t} \right)_q = 0.471 \phi_q + 0.001 \quad (9)$$

380 Eq. (8) had a correlation coefficient of 0.984, where the number of data-points was 156.

381 The deflection-thickness ratios of quadrangular plates subjected to uniform and localised  
 382 loads for all experiments pre-1989 and post-1989 were plotted against the appropriate non-  
 383 dimensional impulse parameters from Eqs. (7) and (8). The graph is shown in Figure 9 and  
 384 comprises results from 356 experiments. A new empirical relationship, given by Eq. (10),  
 385 with a correlation coefficient of 0.94 was obtained from a regression analysis of all 356 data-  
 386 points.

387

$$388 \quad \left( \frac{\delta}{t} \right)_q = 0.506 \phi_q - 0.158 \quad (10)$$

389

390 A statistical analysis showed that both Eqs. (9) and (10) would predict the mid-point  
 391 deflection of a quadrangular plate subjected to either localised or uniform blast load with  
 392 similar probability within one or two plate thickness (72% and 92% respectively), as  
 393 indicated in Table 4. At higher dimensionless numbers, it appears that Eq. (10) would provide  
 394 better prediction.

395

396

### 397 ***3.3 Combining the circular and quadrangular plate data***

398 Nurick and Martin[2] hypothesised that Eqs. (5) and (9) could be used to determine the  
 399 deflection-thickness ratio of any circular or quadrangular plates subjected to impulsive  
 400 loading, provided that the plates do not suffer tearing or shear failure. If a circular and

401 quadrangular plate of equal area, thickness and material properties are subjected to impulsive  
 402 loading over the entire area (that is, uniformly loaded) then the ratio of Eqs. (1) and (7) is:

403

$$404 \quad \frac{\phi_c}{\phi_q} = \frac{2}{\pi^{0.5}} = 1.128 \quad (11)$$

405

406

If Eq. (11) is substituted into Eq. (5) then a new empirical expression is formulated for plates  
 407 of either circular or quadrangular geometry, Eq. (12):

408

$$409 \quad \frac{\delta}{t} = 0.480 \phi_q + 0.277 \quad (12)$$

410

411

Eq. (11) was used to combine all the experimental data for circular and quadrangular plates,  
 412 including the locally loaded tests and those performed at various stand-off distances, with the  
 413 appropriate corrections to  $\phi$  given in Eqs. (2), (8) and (3). The deflection-thickness ratios of  
 414 all plates subjected to blast loads (pre-1989 and post 1989) were plotted against the non-  
 415 dimensional impulse parameter as shown in Figure 10. A regression analysis was performed  
 416 and yielded the empirical prediction given by Eq. (13), which has a correlation coefficient of  
 417 0.92 for 1054 data-points.

418

$$419 \quad \frac{\delta}{t} = 0.446 \phi_q + 0.261 \quad (13)$$

420

A statistical analysis, summarised in Table 5, showed that Eq. (13) provides a better  
 421 correlation for plate prediction than Eq. (12).

423

424

#### 425 4. Concluding comments

426 From the large numbers of experiments conducted since 1989, it has been found that the  
427 failure mode progression of circular and quadrangular plates is similar[3, 9]. The Mode I  
428 deformation profile of uniformly was characterised by a single global dome, whereas locally  
429 loaded plates exhibited a local inner dome atop a global dome profile. Capping and petalling  
430 failures occurred in the centre of locally loaded plates, as opposed to tensile and shear failures  
431 at the boundaries of uniformly loaded plates[3, 9]. The locally loaded plates have been  
432 observed to exhibit tearing at the boundary when the load-plate diameter ratio is increased  
433 above 0.4[13]. Boundary conditions have a significant influence on the tearing and shear  
434 failures of plates due to the difference in in-plane movement achieved with each boundary  
435 condition. Rigid boundaries, such as built-in and welded boundaries, will initiate necking and  
436 tearing failures at lower impulses compared to clamped boundaries[5, 10]. The effect of  
437 “edge sharpness” of the tensile boundary failure of clamped plates showed that filleting the  
438 clamp delayed the onset of tearing by preventing indentation of the plate boundary[6].  
439 Increasing stand-off distance resulted in less localised loading of plates and it was found that  
440 when the stand-off distance exceeds the largest plate dimension, loading could be considered  
441 to be uniform[16].

442

443 The addition of stiffeners reduced the displacements of clamped quadrangular plates  
444 subjected to uniformly distributed blast loading, particularly if they were placed along the  
445 mid-lines of plates[33]. However, the initiation of tearing along the boundary can occur at  
446 lower impulses[33]. In locally loaded stiffened plates, the stiffener placement also affected  
447 the tearing location, with tearing initiating along the stiffener-plate edges[15].

448

449 In parallel with experimental studies, the non-dimensional analysis used by Nurick and  
450 Martin[2] has also been expanded to include the effects of load localisation for quadrangular  
451 plates[14] and the influence of stand-off distance for circular plates[16]. When the new post-  
452 1989 experimental data is plotted in non-dimensional form, the original empirical predictions  
453 proposed in ref[2] are very close to the best fits for the data, with particularly good  
454 correlation observed for circular plates. The data for circular and quadrangular plates has  
455 been combined into one set and a new empirical prediction is proposed in Eq. (12), which is  
456 very similar in form to those previously used. Thus, 25 years on from the original work by  
457 Nurick and Martin[2], it is concluded that this analysis technique is still useful and the  
458 original empirical predictions give good correlation with experiments. *It should be noted that*  
459 *the effects of both strain hardening and strain rate sensitivity have not been specifically*  
460 *considered and that both effects are embedded in the empirical equations.*

461

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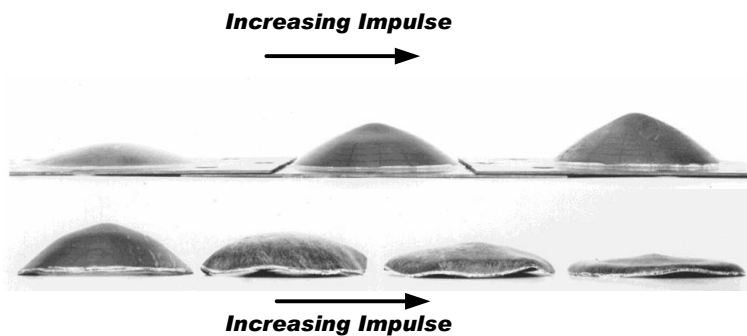
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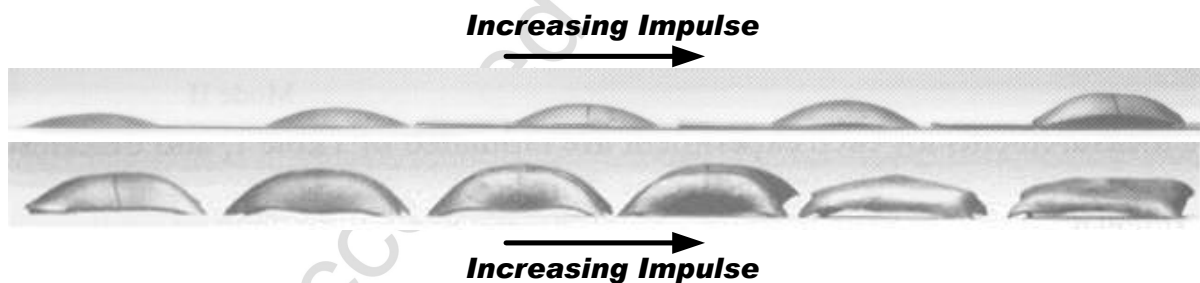


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577 Figure 1: Photographs showing the failure of uniformly loaded circular plates with increasing  
 578 impulse [3]

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583 Figure 2: Photographs showing the failure of uniformly loaded square plates with increasing  
 584 impulse [9]

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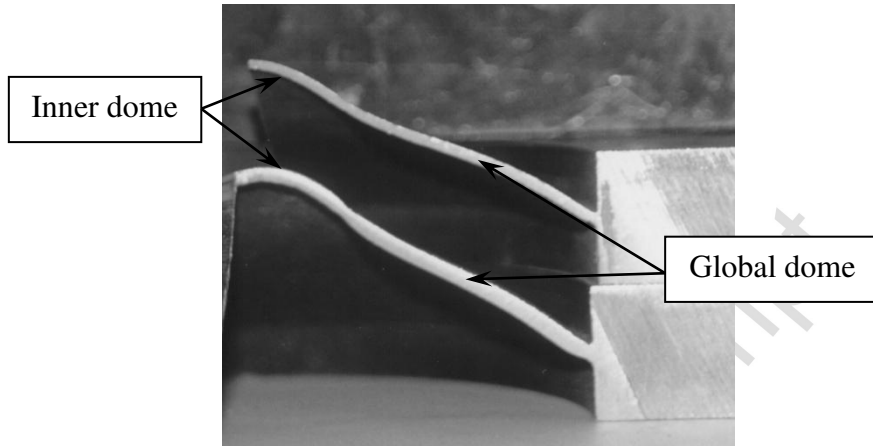
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589 (a) Capping failure (b) Petalling failure (c) Tensile tearing at the  
 590 boundary

591 Figure 3: Photographs of locally loaded circular plates [13]

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594 Figure 4: Photographs of cross-sections from two built-in circular plates subjected to  
 595 localised blast loading [13]

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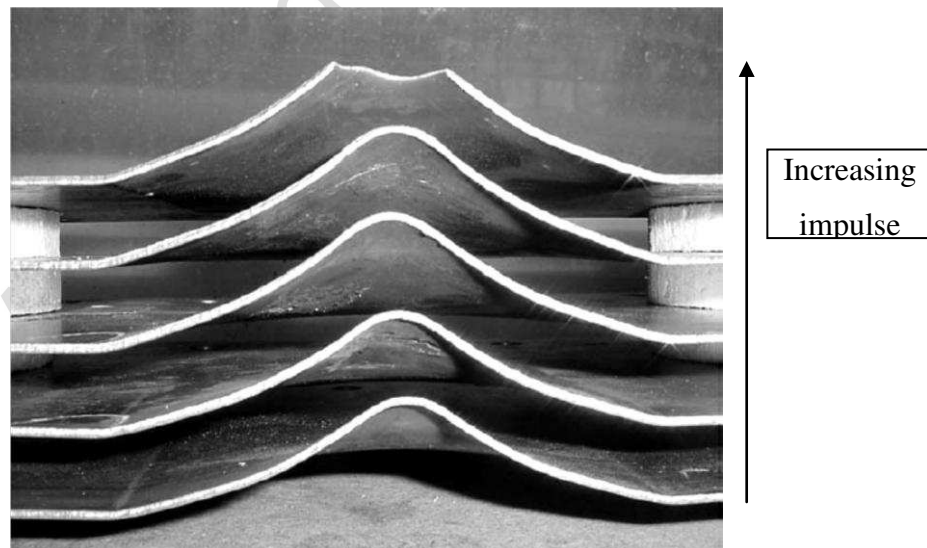
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606 Figure 5: Photographs of cross-sectional profiles from quadrangular plates subjected to

607 localised blast loading [14]

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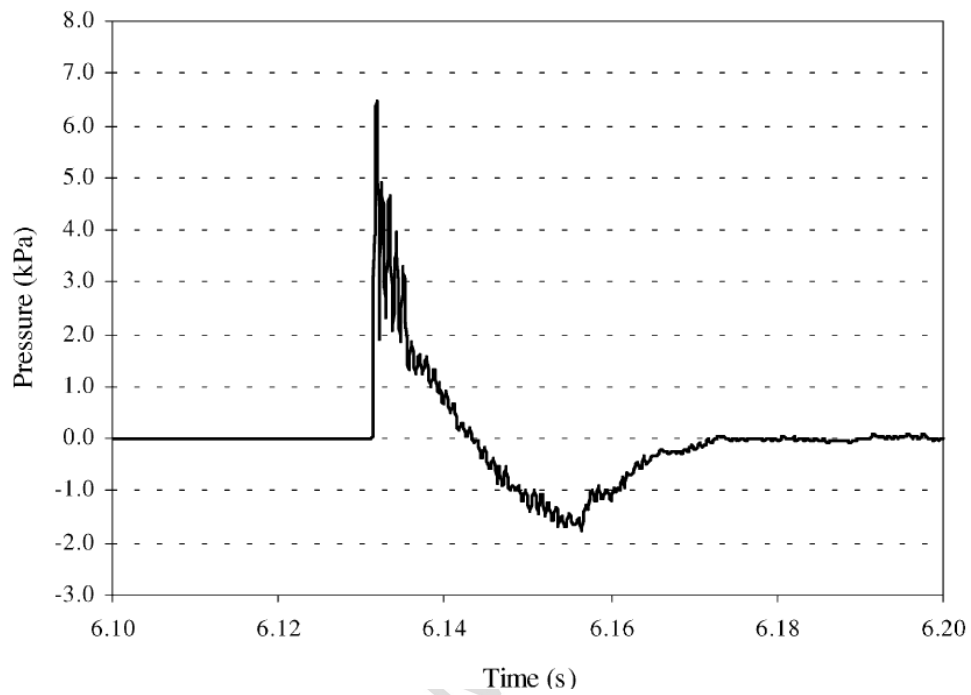


Figure 6: Pressure-time history recorded from a far-field explosion, Jacinto et al. [19]

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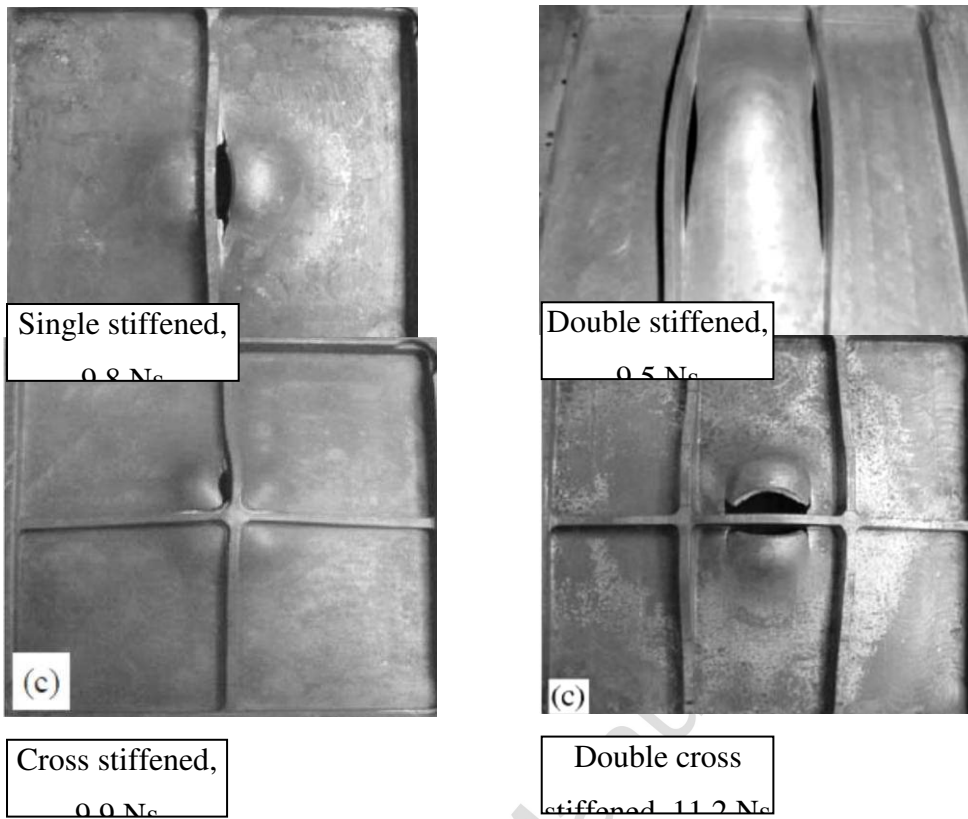
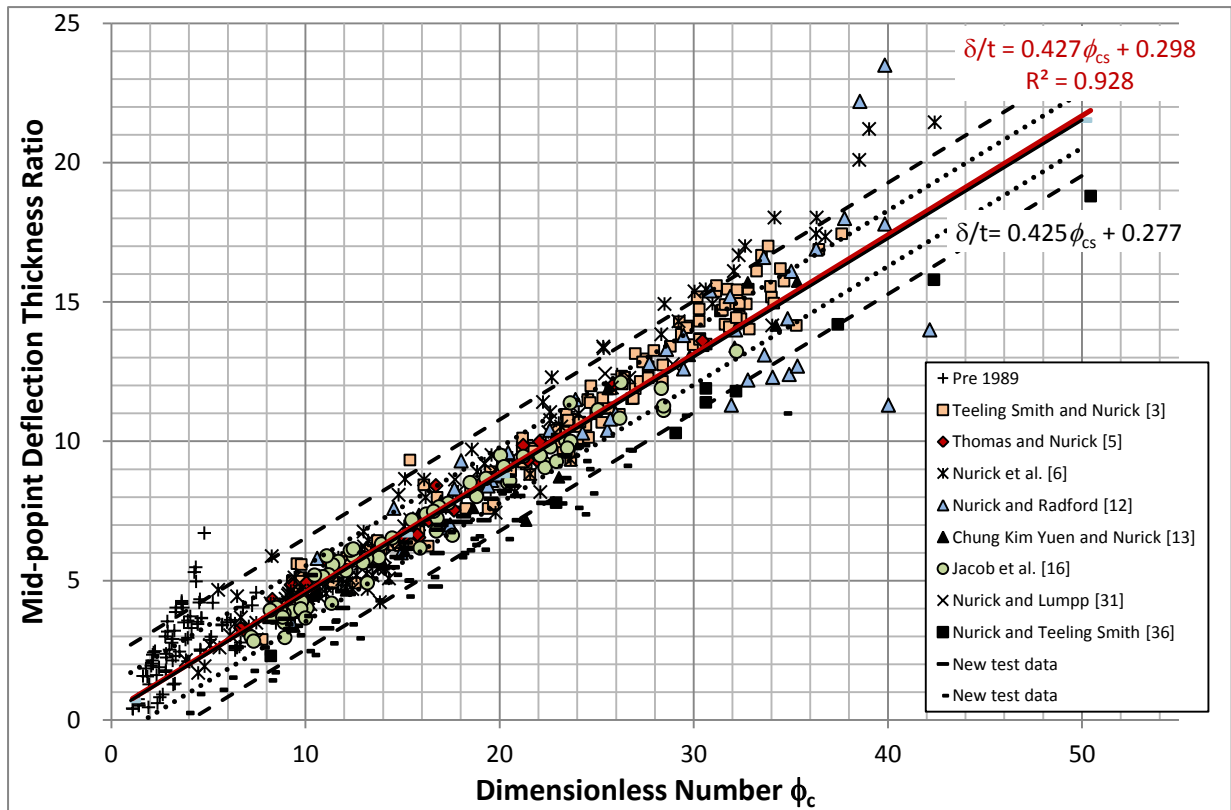


Figure 7: Photographs showing the tearing locations of various stiffened plates subjected to localised blast loading [15]



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641 Figure 8: Graph of displacement-thickness ratio versus non-dimensional impulse for circular

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plates, both pre-1989 and post-1989

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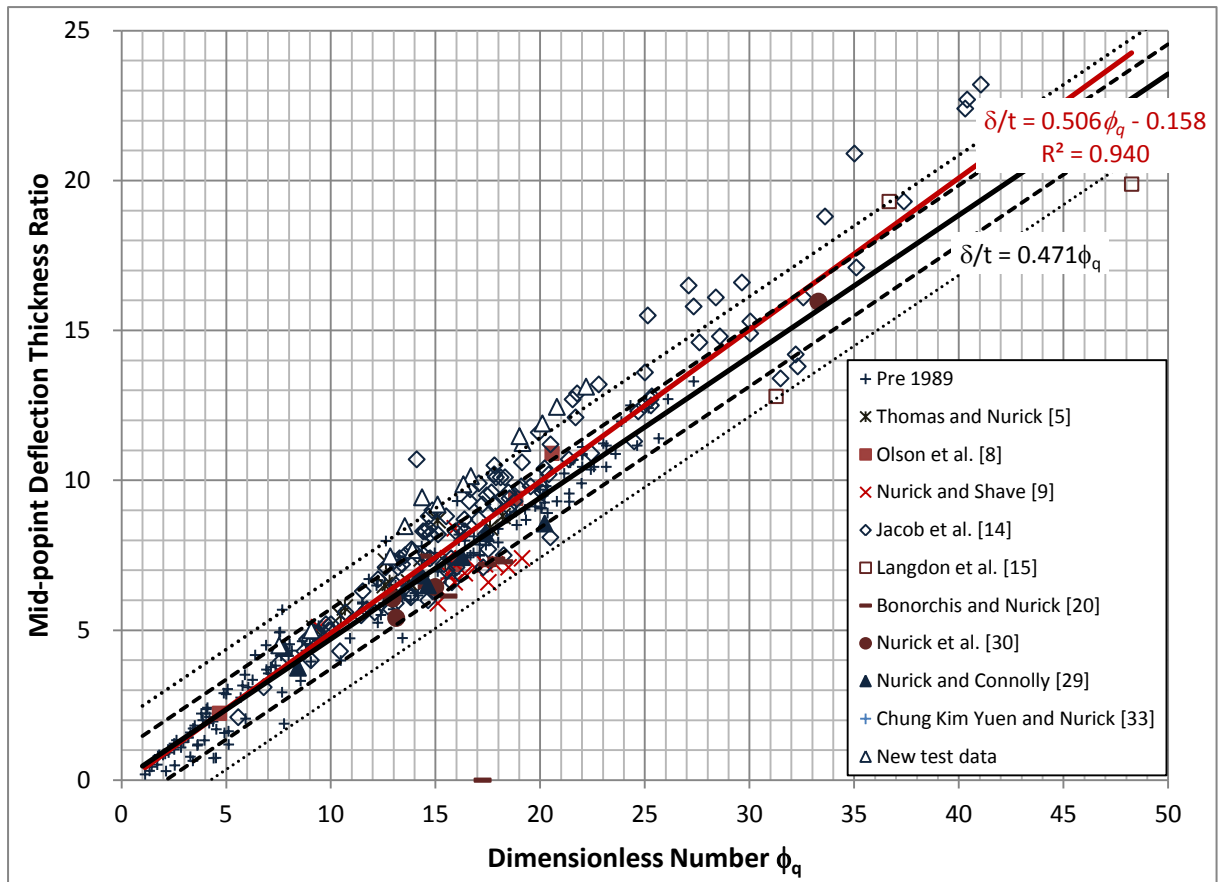
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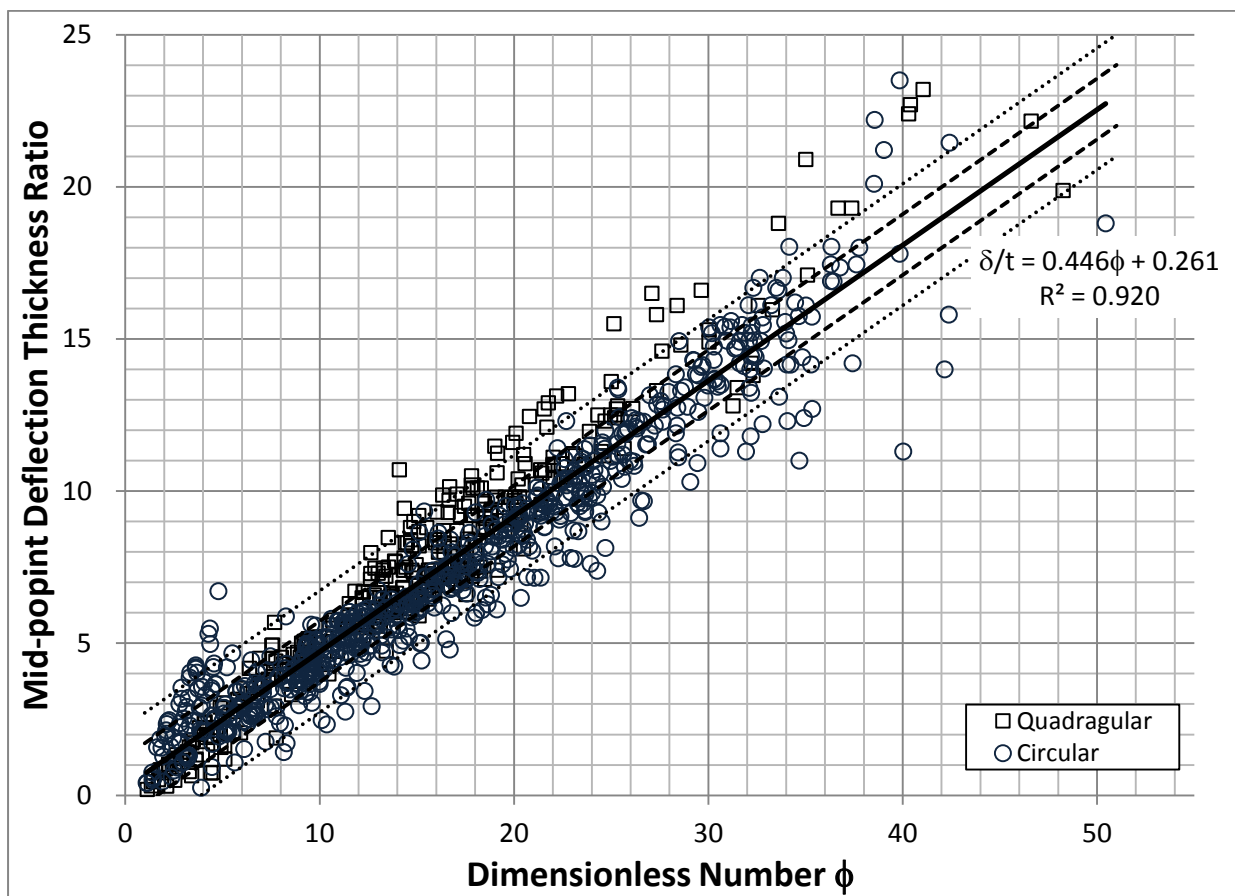
662 Figure 9: Graph of displacement-thickness ratio versus non-dimensional impulse for

663 quadrangular plates, both pre-1989 and post-1989

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Figure 10: Graph of displacement-thickness ratio versus non-dimensional impulse for the combined circular and quadrangular plate data, both pre-1989 and post-1989

Table 1: Summary of experiments performed since 1989 on air-blast loaded metal plates

Load type	Plate type <sup>1</sup>	Reference	Notes	Nominal Plate dimensions (mm)	Year
Uniform	C	Teeling-Smith and Nurick [3]	Failure Modes I, II and III of circular plates	$\varnothing$ 500 - 1000 x 10 - 20	1991
		Thomas and Nurick [5]	Built-in versus clamped boundaries	$\varnothing$ 100 x 1.6	1995
		Nurick et al [6]	Influence of edge sharpness: clamped plates	$\varnothing$ 60 -120 x 1.6	1996
		Cloete et al [7]	Annular and centrally support plates, failure	$\varnothing$ 100 x 1.6	2005
	Q	Olson et al [8]	Failure progression, tearing initiation	89 x 89 x 1.6	1993
		Nurick and Shave [9]	Failure progression, tearing initiation	89 x 89 x 1.6	1996
Bonorchis and Nurick [10]		Varied boundary conditions	188 – 200 x 108 - 120 x 3	2007	
Localised	C	Wierzbicki and Nurick [11]	Failure modes	$\varnothing$ 100 x 1.6	1996
		Nurick and Radford [12]	Failure modes, capping	$\varnothing$ 100 x 1.6	1997
		Yuen and Nurick [13]	Influence of plate thickness, load-to-plate diameter ratio	$\varnothing$ 100 x 1.6 - 3.6	2000
	Q	Jacob et al. [14]	Varied load and plate geometries	160 – 290 x 160 - 290 x 1.6 – 4.0 (different aspect ratios)	2004
		Langdon et al. [15]	Flat and stiffened plates	126 x 126 x 1.6	2005
Stand-off distance	C	Jacob et al. [16]	Influence of stand-off distance on Mode I failure, use of tube to direct blast	$\varnothing$ 106 x 1.9	2007
		Yao et al. [38]	Mild steel, 12.9 – 17.6 mm stand-off distance, dimensionless analysis	160 x 160 x 1.6 -4.0	2015
		Neuberger et al.	Scaling	$\varnothing$ 100 x 1.6	2007

		[17]			
		Neuberger et al. [18]	Springback of armour steel	∅ 1000 x 20	2009
	Q	Jacinto et al. [19]	Boundary conditions, model validation	950 – 1000 x 950 – 1500 x 0.9 – 2.1	2001
		Yuen et al. [21, 22]	Large scale field tests, scaling	500 x 500 x 3-6	2006
Uniform	QS	Schubak et al [25-28]	One and two way stiffeners, model validation	4000 - 4572 x 2438 – 4000 x 6 - 7	1992-1993
		Nurick et al.[30]	Influence of integral stiffeners	89 x 89 x 1.6	1995
		Schleyer et al[32]	Effects of loading direction, in-plane restraint on pulse loaded welded stiffened plates	1000 x 1000 x 2	2003
		Yuen and Nurick [33]	Influence of integral stiffeners	126 x 126 x 1.6	2005
		Veldman [34]	Riveted stiffened plates, pre-pressurisation	508 x 610 x 1.6	2008

681 <sup>1</sup>C = circular, Q = quadrangular, QS = quadrangular stiffened

682 <sup>1</sup>C = circular, Q = quadrangular, QS = quadrangular stiffened

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686 Table 2: Descriptions of failure modes for plates subjected to uniformly and locally  
 687 distributed blast loading, according to Jacob et al [16]

<b>Failure Mode</b>	<b>Description</b>	<b>Uniform loading</b>	<b>Localised loading</b>
Mode I	large inelastic deformation	✓	✓
Mode Ia	large inelastic deformation with necking around part of the boundary	✓	
Mode Ib	large inelastic deformation with necking around the entire boundary	✓	✓
Mode I <sub>tc</sub>	large inelastic deformation with thinning in the central area		✓
Mode II*	large inelastic deformation with partial tearing around part of the boundary	✓	
Mode II*c	partial tearing in the central area		✓
Mode II	tensile tearing at the boundary	✓	✓
Mode IIa	increasing mid-point deflection with increasing impulse with complete tearing at the boundary	✓	
Mode IIb	decreasing mid-point deflection with increasing impulse with complete tearing at the boundary	✓	
Mode IIc	complete tearing in the central area – capping		✓
Mode III	transverse shear failure at the boundary	✓	
Petalling			✓

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690 Table 3: Statistical variation of deflection-thickness ratio for circular plates subjected to blast  
 691 load for all data

	Number of data points	$\pm 1$ plate thickness	$\pm 2$ plate thickness
$\phi_c$ , Eq. (4)	699	74%	90%
$0 \leq \phi_c \leq 25$	559	80%	93%
$\phi_c > 25$	140	49%	77%

692

693 Table 4: Statistical variation of deflection-thickness ratio for quadrangular plates subjected to  
 694 blast load for all data

	Number of data points	$\pm 1$ plate thickness	$\pm 2$ plate thickness
$\phi_q$ , Eq.(8)	354	72%	94%
$0 \leq \phi_q \leq 25$	320	77%	96%
$\phi_q > 25$	34	47%	65%
$\phi_q$ , Eq.(9)	354	73%	92%
$0 \leq \phi_q \leq 25$	320	74%	97%
$\phi_q > 25$	34	44%	65%

695

696 Table 5: Statistical variation of deflection-thickness ratio for the combined circular and  
 697 quadrangular plate data

	$\pm 1$ plate thickness	$\pm 2$ plate thickness
Eq. (12)	61%	88%
Eq. (13)	71%	89%

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