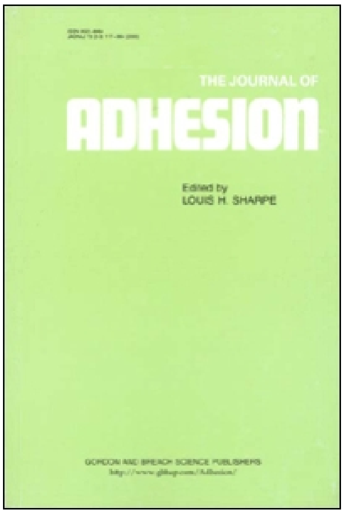

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THE BEHAVIOUR OF ADHESIVELY BONDED BEAMS VERSUS THEIR WELDED EQUIVALENT

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The study aims to produce a design guide for the calculations of stresses and deflections of adhesively bonded beams fabricated from steel adherends using a structural epoxy adhesive. Such design calculations already exist for welded but not for bonded beams. Small models based on beams with a T-section profile, at various beam lengths, are formulated. A key to these calculations is the determination of the adhesive/adherend interface factors/coefficients, to correct the estimated values of stress and deflection from three-point bending conditions. This article presents the methodology for evaluating bonded beams in relation to equivalent welded (solid) beams. This includes mechanical testing, an analytical method based on beam and sandwich theory, and finite element techniques. Results from these techniques are presented and compared and values of the coefficients for T-section beams are determined.

INTRODUCTION

There is a potential to use structural epoxy adhesives in the steel fabrication of stiffened panels/beams for ships and similar constructions. This complements fusion welding where T, L, I, and Z shape stiffeners are welded to plates. Equivalent bonded panels may be designed to resist lateral loading, resulting in bending stresses in the adherends and shear stress within the adhesive [1]. Very few studies investigated the bonded beam behaviour under bending but at a limited depth [2–4]. These also deal with either thin adherend applications or low Young's

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modulus adherends (lower than for steel). In bending of composite laminates the actual in-plane bending and shear stresses might be modified by introducing an interface coefficient/correction factor [5]. This concept will be utilised in this study and introduced in bonded beams. The use of classical beam theories [6, 7] to determine stresses and deflections in bonded sections could be useful but these may underestimate stresses. Welded panels under bending are normally designed to bending stress and/or deflection limits and, hence, these limits determine their dimensions.

The dimensions of structural parts in the case of marine and similar construction affect weight and fabrication cost [8]. Figure 1 illustrates schematic designs for welded steel panels, of the same flexural rigidity, D, which result in different weight and fabrication costs. The design in Figure 1a is based on using thick plates (normally greater than 8 mm), large stiffeners, and wide spacing between stiffeners, while the design in Figure 1b uses thinner plates, smaller stiffeners, and closer spacing. The choice between the two depends on the main design requirement, *i.e.*, low cost or minimum weight. The fabrication cost of the minimum weight design is high and is largely associated with controlling thermal distortion of thin steel plates, typically 6–8 mm (relatively thin in ship construction). Adhesive bonding perhaps could

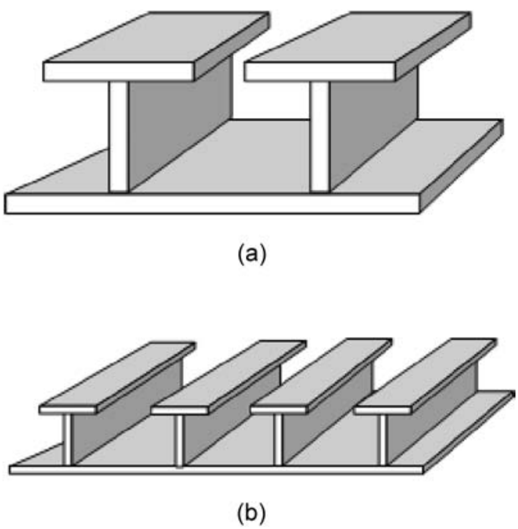

FIGURE 1 Welded panel design. (a) Low cost and heavy. (b) High cost and light.

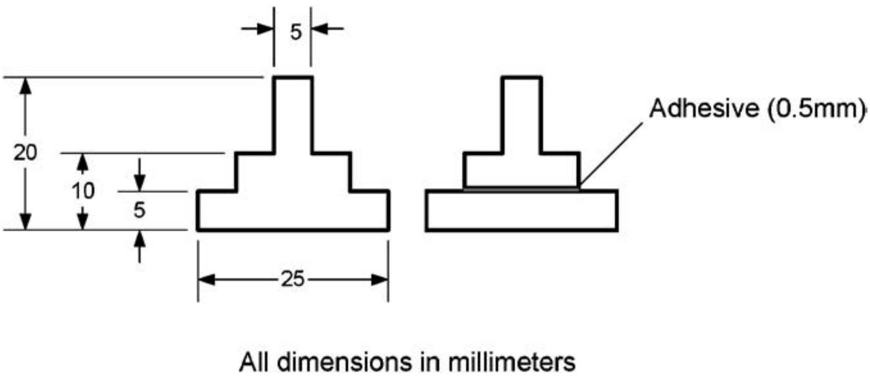

FIGURE 2 Solid and bonded beam sections.

meet the two requirements due to absence of thermal distortion and perhaps cheaper fabrication cost [9].

This study aims to investigate thick beam behaviour in depth and to produce a design guide to calculate stresses and deflections in adhesive bonded steel beams. Models represent bonded and welded beam sections; typically 25 mm wide and 20 mm high are produced (Figure 2). The beams with various spans (50–250 mm) are tested in three-point bending with simply supported boundary conditions. The maximum stresses and deflections under quasi-static loading are measured and compared. Besides the experiments, the study uses sandwich beam theory and finite element analyses (FEA) techniques. Results from these are presented and discussed. A key to these results is the determination of correction factors, which can be used in conjunction with beam theory that is widely used for welded beams and may not be suitable for bonded equivalents. These factors may incorporate the various design parameters of the beams and may be extended to panels.

EXPERIMENTS

Ten T-section specimens were fabricated from cold-rolled bars of low carbon (mild) steel grade, designation 080M15 according to British Standard 970 : 2001. The specimens include five with solid sections and five with adhesively bonded sections. Beam spans of 50 mm, 75 mm, 150 mm, 200 mm, and 250 mm were considered for the simply supported boundary conditions.

Solid beam sections were machined from the steel bars to represent the welded beam models. This was to simplify the production and control dimensions, which are more difficult to achieve by welding small specimens. Full penetration welding is another assumption in this study, considered again for simplification. The bonded beams sections were produced by bonding machined stiffeners (Ts) to plates (Figure 2). The bonding surfaces of the bonded specimens/beams were prepared to BS5350; Methods of tests of adhesives. The bonding procedures included solvent degreasing and grit-blasting prior to the application of the adhesive. The bonding was achieved using a single part epoxy adhesive, AV119, from Vantico UK Ltd. (Cambridge, UK). An adhesive bondline nominal thickness of 0.5 mm was used for all the specimens. The thickness was controlled by wires that were placed outside the bond test area. The adhesive was then cured at 160°C for 30 min and the bondline thickness was verified after curing.

The specimens were mechanically tested under monotonic loading at ambient temperature and the maximum load applied in each case corresponds to 90% of the yield strength of the stiffener. This was estimated by using the bending beam theory for solid sections. None of the test specimens failed in compression buckling of stiffeners/webs. The central deflection was measured by a displacement transducer with a range of ± 0.5 mm. The longitudinal bending strain was measured using strain gauges at the lower surface of the beam. Figure 3 shows the test set up.

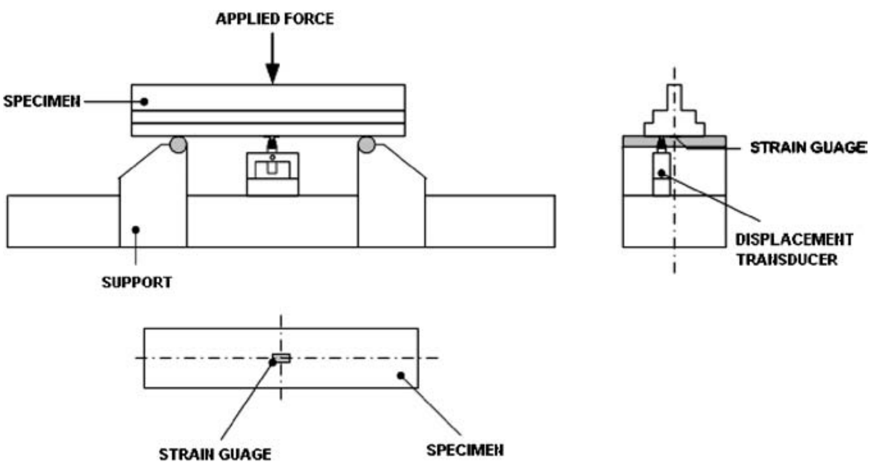

FIGURE 3 Setup for three point bending experiments.

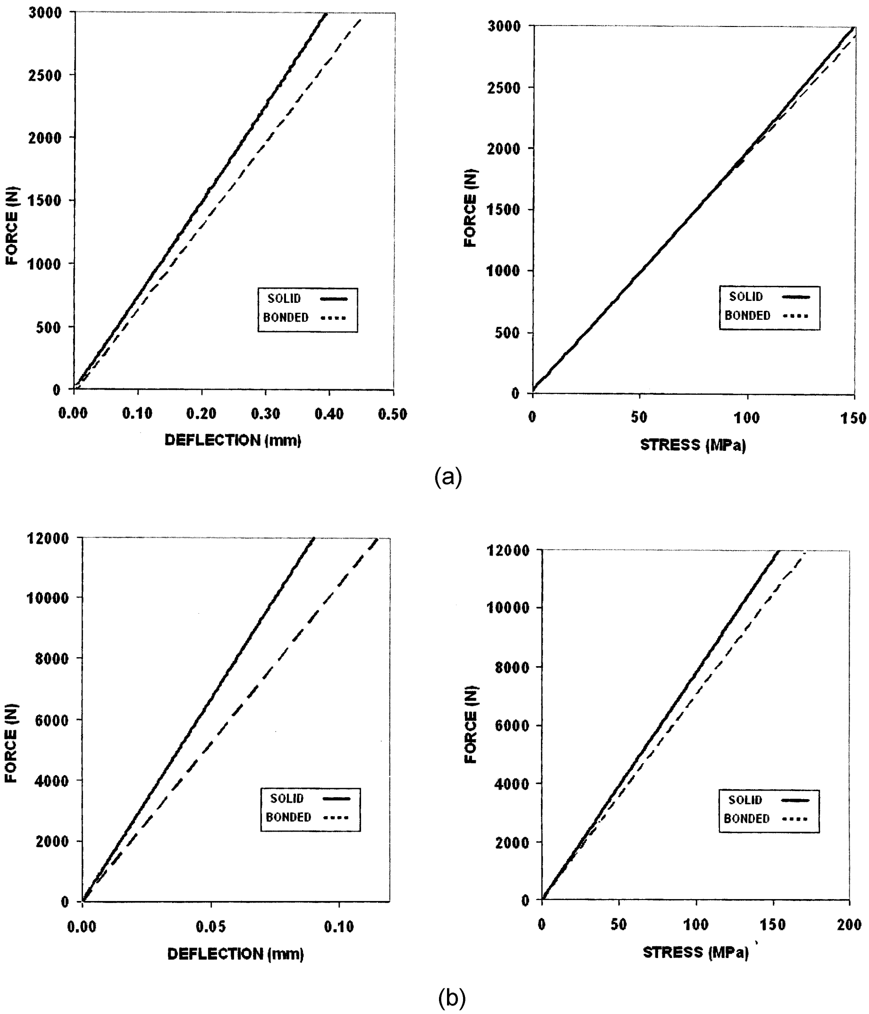

FIGURE 4 Bending test curves for T-section beams. (a) 200 mm span, (b) 50 mm span.

Typical results from these tests are shown in Figure 4. From these it can be noticed that bonded specimens generally show higher central deflections and bending strain/stress than their solid equivalents. These differences are more pronounced for the shorter beams as shown (50 mm span). However, with shorter beams there were accuracy problems in measuring deflections due to the specimens' indentation by the loading mandrel.

ANALYSES

In addition to the experiments, both numerical and theoretical analyses were used for the T-section models (Figure 2). The numerical modelling for the 10 models was based on finite element analyses (FEA) using MSC PATRAN preprocessor (finite element modeller) and ABAQUS postprocessor (finite element analyser), and 20-noded hexahedron cube elements were chosen for the mesh. In the five bonded models, the 0.5 mm adhesive thickness was modelled with two layers through thickness. All the models were meshed with the same degree of refinement to obtain consistent results. Various refinements were considered for the mesh of the models, especially at the centre of beams, but these have little effect on the overall behaviour and stress level. Elastic isotropic properties for the adhesive and adherends were considered. Manufacturer's adhesive properties for a Young's modulus and Poisson's ratio of 3.5 GPa and 0.37, respectively, were used. Standard properties were used for the mild steel. A concentrated load of 2kN–12kN was applied in simply supported boundary conditions. Figure 5 shows a typical mesh for the bonded T-section beam (250 mm span) under exaggerated displacement conditions. Figure 6 shows typical stress distributions and deflection for the beam along its span. The bending stress is taken at the lower plate surface, *i.e.*, adherend. The transverse bending shear stress is along the interface between the stiffener flange and the upper plate, *i.e.*, along the adhesive bondline in the case of the bonded model.

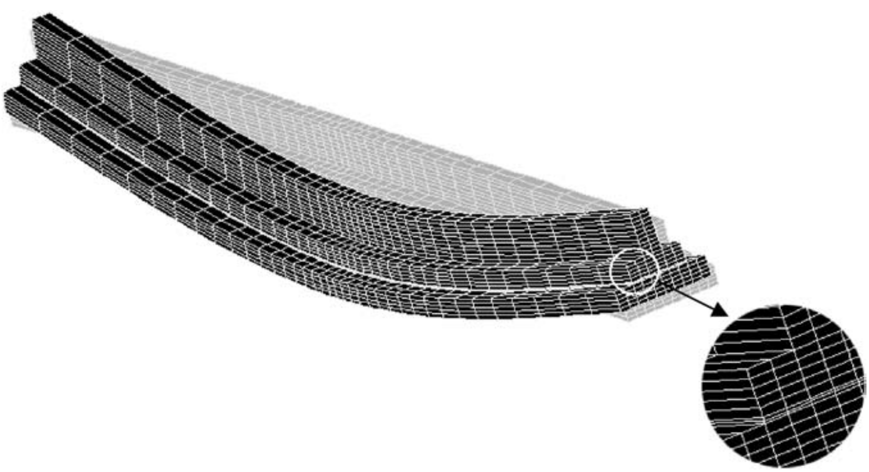

FIGURE 5 A typical mesh details for a bonded T-section beam model.

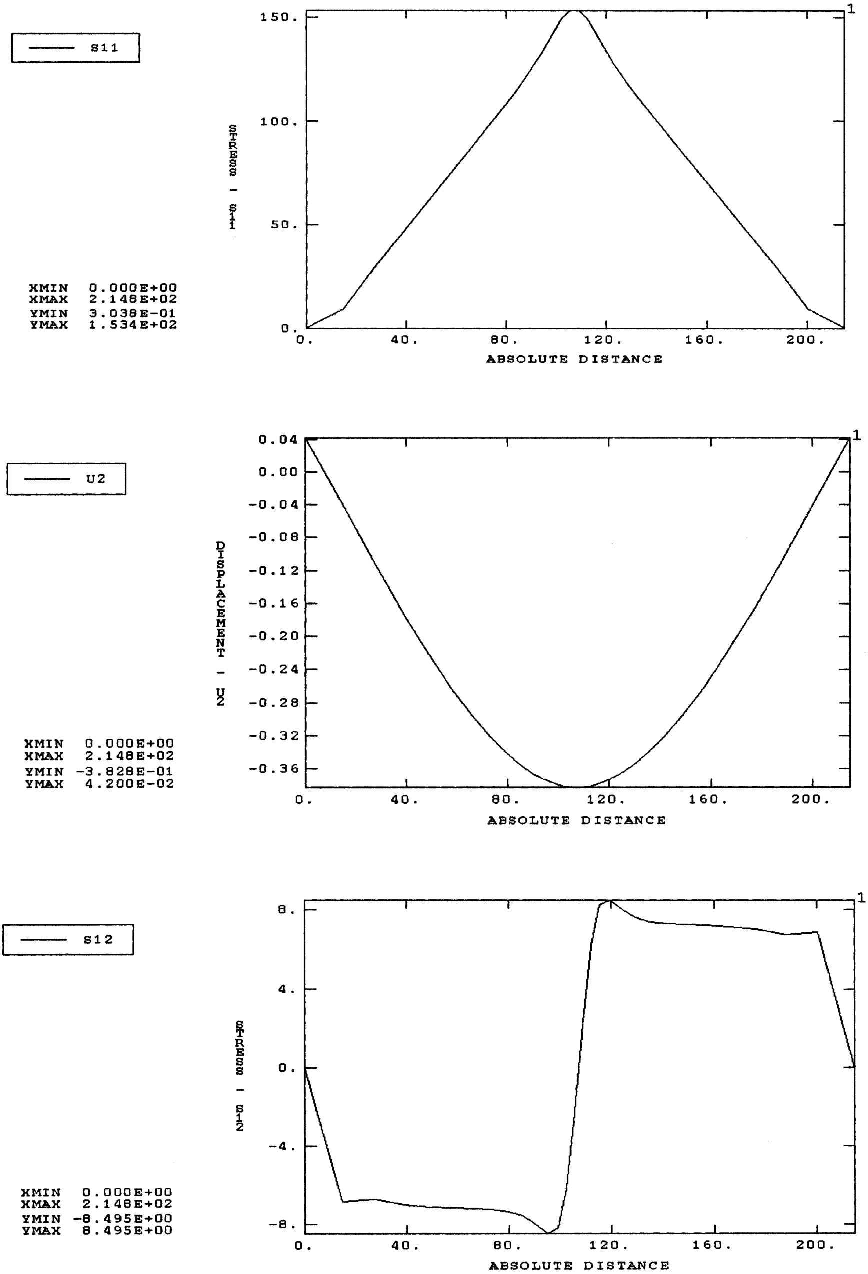

FIGURE 6 Deflection, bending, and shear stress distribution computed via FEA along the span of the beam.

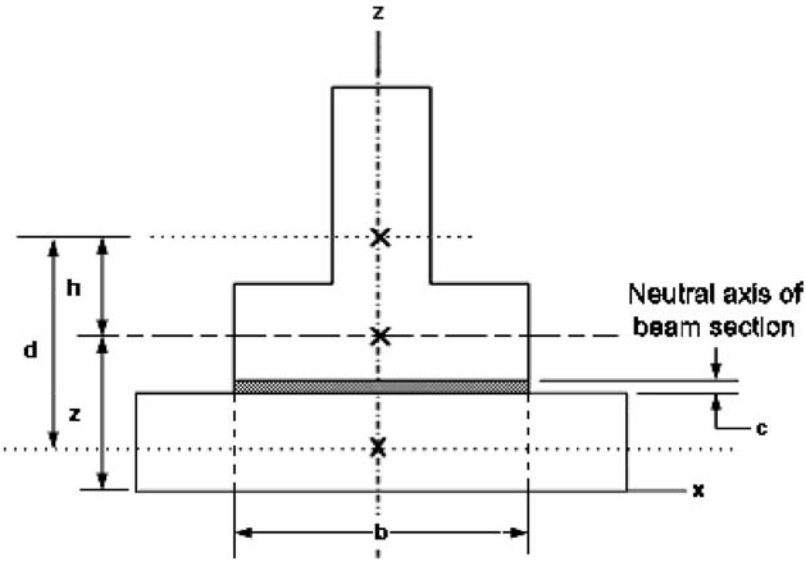

FIGURE 7 Details of bonded/sandwich section.

The standard beam theory was applied to the solid sections, while the sandwich theory [10] was applied to the bonded sections. The basic sandwich beam theory is based on two faces and a core. The core was replaced by the adhesive layer, while the upper face was replaced by the stiffener. The distance between the centres of the two "faces" is given by the symbol d, as shown in Figure 7. Thus, the following bending stress, shear stress, and deflection are used for the bonded beam sections:

$$\sigma_b = \frac{M^* z^* E_s}{D} \tag{1}$$

$$\tau_{\max} = \frac{0.5^* F^* E_s^* h^* A_s}{D^* b} \tag{2}$$

$$\delta_b = \frac{F^* L^3}{48^* D} + \frac{F^* c^* L}{G_a^* b d^{2*} 4} \tag{3}$$

RESULTS AND DISCUSSION

Table 1 shows a summary of all results. There seems to be a reasonable agreement among the values of bending stress estimated from

TABLE 1 Results (Analytical, Numerical, and Experiment)

Section type	Length between supports (mm)	Applied force (N)	Analytical results			Numerical results			Experimental results	
			σ (MPa)	τ^* (MPa)	δ (mm)	σ (MPa)	τ^* (MPa)	δ (mm)	σ_{ten} (MPa)	δ (mm)
	250	2400	149.5	6.1	0.584	153.4	6.8	0.598	145.6	0.616
Solid T-section beam	200	3000	149.5	7.7	0.374	153.4	8.5	0.383	151.7	0.393
(25 mm $\times$ 20 mm)	150	4000	149.5	10.2	0.210	155.6	11.4	0.221	155.8	0.251
	75	8000	149.5	20.4	0.053	164.8	22.6	0.066	149.7	0.102
	50	12000	149.5	30.7	0.023	169.0	32.4	0.032	153.8	0.092
	250	2400	149.8	6.1	0.597	155.9	6.1	0.620	155.8	0.664
Bonded T-section beam	200	3000	149.8	7.7	0.387	156.2	7.6	0.404	153.8	0.451
(25 mm $\times$ 20 mm)	150	4000	149.8	10.2	0.223	158.9	9.8	0.240	153.8	0.278
Ahesive thickness = 0.5 mm	75	8000	149.8	20.4	0.065	170.0	16.8	0.082	155.8	0.121
	50	12000	149.8	30.7	0.036	178.1	19.5	0.045	172.2	0.115

*Shear stress is taken at the interface between adhesive and adherend of bonded beams or at the corresponding location of the solid beams.

the three methodologies, including between the experiments and the numerical (FEA). However, the stresses from the analytical methods based on beam and sandwich theory do not show a difference in the bending stresses between bonded and solid sections. From the FEA results, the shear stress in the adhesive interface with the adherends of the bonded models differs significantly from the corresponding shear stress in the solid models, especially for shorter spans. In addition, the deflection is generally higher in the bonded specimens.

As mentioned earlier, there is an experimental limitation associated with local indentation of the specimens. This is more noticeable for the short spans (50 mm and 75 mm) which are subjected to significant shear forces. This may question the reliability of the deflection results from the experiments. However, such problems apply to both solid and bonded models and, therefore, the comparative results are useful. Because of the experimental and theoretical limitations, the numerical results are more consistent than the others and, hence, the conclusions should focus on them.

The interface coefficients/factors may be represented by the ratio between the stresses and deflection values (numerical) for bonded sections and those of their solid equivalents. Thus, the following general equation for the interface coefficients of deflection, bending stress, and shear stress are used:

$$f_\delta = \frac{\delta_b}{\delta_s}, \quad f_\sigma = \frac{\sigma_b}{\sigma_s}, \quad f_\tau = \frac{\tau_b}{\tau_s} \tag{4}$$

From Table 1 the curves for the above coefficients are plotted in Figure 8. These show that the coefficients for deflection and bending stresses are higher than unity, especially for deflection (depending on spans). The shear stress coefficients, however, are significantly lower than unity, and this means that the use of the sandwich beam theory could overestimate the level of shear stress in the adhesive. Similar curves are expected from the experimental results, but this is limited to the bending stress and deflection. It is difficult to measure experimentally the shear stress/strain along the location of the bondline.

Since the deflection results for bonded sections from the FEA are comparable with those from the sandwich theory, Equations (1) to (4) may also be used to generate equations for the interface coefficients as a function of beam geometry and materials, including T-section beam details and adhesive thickness. For example, the deflection equation is

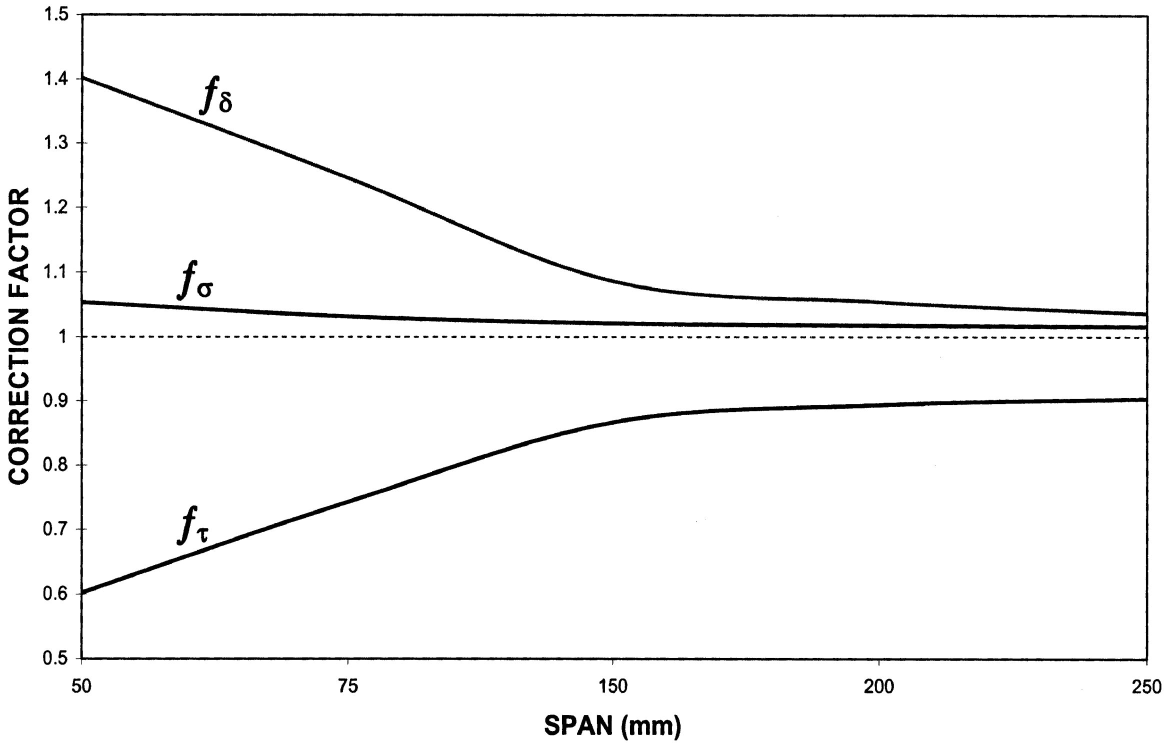

FIGURE 8 The interface coefficients deduced via FEA.

$$f_\delta = 1 + \frac{E_s^* A_s^* h^* c}{12^* L^{2*} G_a{}^* d^* b} \tag{5}$$

It appears that the difference in the behaviours between the two section types (Table 1) are more pronounced for the deflection and shear stress than for bending stress, especially for shorter beams. The adhesive shear strains for the shorter bonded beams are higher than those for the longer beams due to the higher applied forces. Another factor that could influence the bending behaviour is the profile of the section (*e.g.*, Z and L), and this is currently under investigation. Also, initial observation suggests that the behaviour of bonded beams under plastic deformation could result in even higher differences in stresses and deflection in comparison with welded equivalents. Beyond the elastic limit, plastic deformation in the bonded beams can result in critical adhesive cleavage stresses at the ends of the beams. These are also future investigations of this research.

The interface coefficients for stresses and deflections obtained from Figure 8 could be used in conjunction with the standard solid beam theory to determine the levels of stresses and deflections in large bonded panels. It is possible to generate polynomial equations from these curves and relate them to the ratios of deflection to span and to loading to flexural rigidity of the panels. This is a subject for further work. Structural panels are more relevant to the short span beams than longer ones in this study. Therefore, this means that bonded panel designs will produce a lower stiffness than their welded equivalents. A lower stiffness implies that bonded structures would be slightly heavier than their welded equivalents. This, however, could be compensated for by the absence of residual welding stresses in the plating and the freedom to bond thinner plates with closer stiffeners, without the technical and economic problems associated with controlling thermal distortion during welding of such geometries. Bonded stiffeners would also increase the effective breadth of panels due to the wide flange attachment and absence of distortion [9].

CONCLUSIONS

This study demonstrated that bonded beams behave differently from their welded/solid equivalent in terms of levels of stresses and deflections. Simple beam theory has limitations for bonded beams, but the sandwich beam theory is more useful for short beam calculation. From experiments, FEA, and analyses the following conclusions are reached with reference to T-section beams:

- Very long bonded beams behave similarly to their solid/welded equivalent.
- Short bonded beams differ from their solid equivalent and produce higher bending stress and deflection.
- Shear stress in a bonded T-section beam is significantly lower than for a solid one, depending on span.
- The interface coefficients for small beams could be extended to bonded panel design.
- Further studies are necessary to understand short beam behaviour and plastic deformation.

NOMENCLATURE

σ_b	maximum bending stress at lower bonded beam surface, MPa
σ_s	maximum bending stress at lower solid beam surface, MPa
δ_s	central deflection of solid beam, mm
δ_b	central deflection of bonded beam, mm
$\tau_{\max}$	maximum shear stress at adhesive location, MPa
ν	Poisson's ratio
S11	numerical bending stress in the x-direction, MPa
S12	numerical shear stress, MPa
U2	numerical central deflection, mm
D	flexural rigidity, N.mm^2
E_s	Young's modulus of steel, MPa
F	load, N
G_a	shear modulus of adhesive, MPa
I	2nd moment of inertia of beam section, mm^4
L	span of the beam supports, mm
M	bending moment, N.mm
b	width of stiffener flange, mm
c	thickness of adhesive, mm
f_δ	interface coefficient for deflection
f_σ	interface coefficient for bending stress
f_τ	interface coefficient for shear stress
h	distance from neutral axis to centroid of stiffener, mm
z	distance from neutral axis to lower beam section face, mm
A_s	section area of stiffener, mm
Q	First moment of stiffener section area, mm^3

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