IMPACT PERFORMANCE OF MODEL SPOT-WELDED STAINLESS STEEL STRUCTURES

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ABSTRACT:

As part of a wide ranging investigation into the structural performance of spot-welds in austenitic nickel-containing stainless steel, the behaviour of simple structures subjected to drop weight tests, generating strain rates in the range $10\ s^{-1} < \dot{\varepsilon} < 100\ s^{-1}$, has been investigated. The motivation for this work arose from a report of a collision of railway vehicles in which stainless steel spot-welds were believed to have performed unsatisfactorily under impact. A programme of experimental work has shown that, in general, stainless steel structural sections, with appropriately sized and positioned spot-welds, can absorb significantly more energy than carbon steel structures and, moreover, the performance can be adequately predicted by non-linear finite element modelling. Brief mention is also made of comparisons between the behaviour of spotwelds and laser-welds: the latter are particularly useful since access from only one side is required to manufacture the joint.

1. INTRODUCTION

Stainless steel has been widely used for rail vehicle bodyshell design for many years owing to its corrosion resistance, low life-cycle cost, high strength-to-weight ratio and fire resistance. However, with ever more demanding requirements for improved passenger safety, the impact performance of the bodyshell structure has become increasingly important.

Furthermore, the behaviour of spot-welded stainless steel structures subjected to impact loading has been called to account following a train collision in 1988 where the poor performance of the joints was alleged to have contributed to the loss of struc-tural integrity [Private Communication (1995)]. This led one particular train operator to ban spotwelded joints from the energy absorbing regions of new stainless steel vehicles. However, to the knowledge of the authors, this has yet to be supported by any publicly reported scientific investigation. Furthermore, in comparison with carbon steel, where extensive work is reported in the literature regarding suitable welding conditions, nugget diameters, strength and mode of failure, little work pertaining to austenitic stainless steels has been undertaken.

This paper describes such an investigation, beginning with an assessment of existing spotwelding and laser-welding practice for stainless steel using single weld specimens before considering structural sections subjected to quasi-static and impact loading. Finally, the impact behaviour of spotwelded structural sections is modelled using nonlinear finite element analysis.

2. AUSTENITIC STAINLESS STEEL

Two grades of commercial austenitic stainless steel were chosen: AISI type 301L was procured as 1.5 mm and 2 mm thick sheets in the 2B, MT and HT conditions. The 2B is, essentially in the fullyannealed condition (the material undergoes approximately 0.3 % cold work during 'skin-pass' rolling to achieve the surface finish, though this may be assumed negligible). MT (medium tensile) and HT (high-tensile) represent the temper 1/4 hard and 1/2 hard conditions respectively, produced by controlled amounts of cold rolling.

The second type, the 304L grade was obtained in the 2B and work-hardened conditions (although the carbon content for the latter was outside the 0.03%

required for the L designation). Both conditions were obtained as 1.5 mm thick sheets. Chemical compositions for all five materials in 1.5 mm sheet are shown in Table 1.

Mechanical properties were obtained from tensile tests carried out on the candidate materials in the direction of rolling and are listed in Table 2. Carbon steel was also added for comparative purposes.

Table 1. Chemical Composition

Material Grade	Condition	Chemical	Composition / %		
		C	Cr	Ni	N
301L	2B	0.023	17.48	6.66	0.15
301L	MT	0.021	17.20	6.56	0.13
301L	HT	0.023	17.48	6.66	0.15
304L	2B	0.020	18.29	9.23	0.04
304	HT	0.034	17.7	8.1	0.05

Table 2. Mechanical Properties

Material	0.2 % Proof Stress (MN/m^2)	Tensile Strength (MN/m^2)	Elongation A_{50} (%)
301L LT 400		845	52
301L MT600		995	34
301L HT900		1120	26
304L LT 310		620	56
304 HT 470		820	46
Carbon steel 245 (BS 4360 43A)		345	44

3. WELDING TECHNIQUE

3.1 Resistance Spot-welding

Resistance spot-welding (RSW) is a process in which two sheets of material are joined together using the heat generated by the resistance to the flow of electric current through the workpiece, melting a 'nugget' which, when cooled, fuses the sheets together .

The relevant British Standard [BS 1140 (1993)] recommends that spot-welds should be of sufficient quality that failure occurs in the material surrounding the weld ('plug-pull' or 'heat-affected zone (HAZ)' failure) rather than across the weld itself ('inter-facial' or 'weld' failure) in the shear test, cross-tension test, peel and chisel tests for sheet thickness up to 1.5 mm. This mode ensures that the optimum weld strength is achieved and that maximum energy is absorbed during failure.

The type of failure, however, is known to depend on the size of the weld nugget and, therefore, the relevant British Standard recommends minimum nugget diameters depending upon the sheet thickness according to the relation:

$$d = 5\sqrt{t} \qquad (1)$$

where d is the weld nugget diameter and t is the sheet thickness in mm.

This relation is based upon work specifically pertaining to carbon steel, rather than stainless steel. However, welding guides for stainless steel [such as AISI (1993)] suggest that the nugget diameter should be maintained to the same size as that for carbon steel and suggest appropriate welding parameters in order to achieve the weld shown in Figure 1.

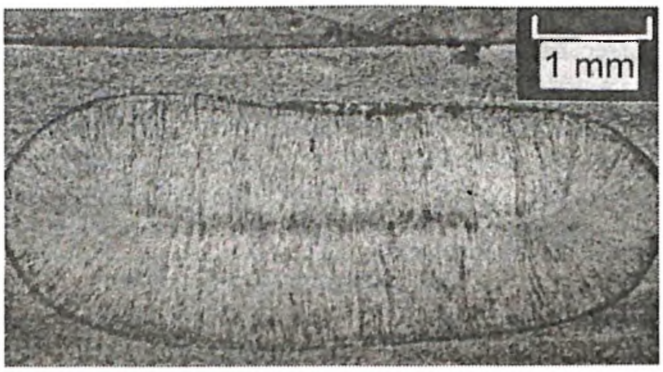

Figure I. Typical weld nugget in austenitic stainless steel.

It is important, however, to note that, unlike carbon steel which can be hardened by heat-treatment, austenitic stainless steels achieve their strength through cold-working which is subsequently lost during heating. Consequently, carbon steel spot-weld nuggets exhibit higher hardness values than the parent material, whereas stainless steel nuggets are significantly softer than the parent material, as shown in Figure 2.

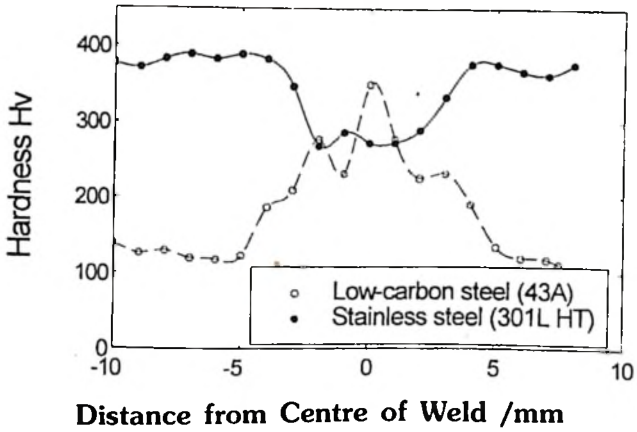

Figure 2. Hardness profiles across carbon and stainless steel spot-welds.

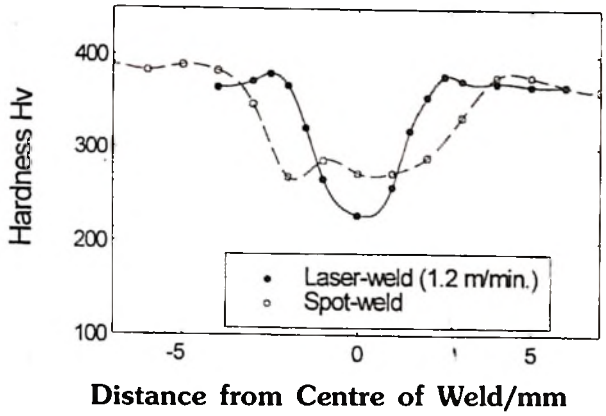

Figure 4. Hardness profiles for laser and spot-welded joints.

3.2 Laser-welding

A laser beam is an 'intense, coherent beam of monochromatic light amplified several hundred times such that it can melt a hole in any opaque material' [AISI (1993)]. Welding can therefore be achieved by passing a laser beam along a lap or butt joint at a pre-determined speed causing a small, contained region of material to melt and fuse the sheets. The subsequent rapid cooling ensures that the heat affected zone is small, as shown in the cross-section and hardness profile comparison shown in Figures 3 and 4 respectively. Laser-welding is fast, efficient, gives excellent seam qualities and, unlike resistance spot-welding, requires access from only one side of the joint.

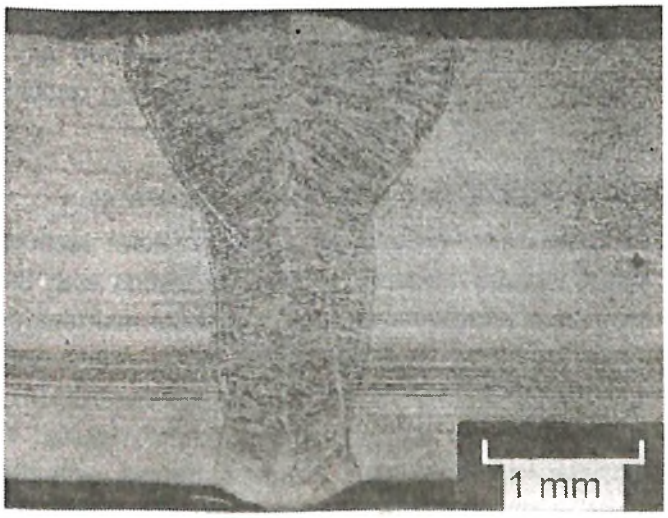

Figure 3. Laser-welded joint in stainless steel

4 FAILURE MODE OF SINGLE SPOT- WELDED AND LASER-WELDED SPECIMENS

The failure mode of single spot-weld and laser-weld specimens was investigated using simple static tests. Spot-welds were produced using the recommended parameters to achieve nugget diameters according to the $5\sqrt{t}$ criteria. A transverse stitch laser-weld configuration with equivalent spot-weld area was used to compare the two techniques.

4.1 Specimen design

In order to examine the behaviour of spot-welded and laser-welded joints in various grades and conditions of austenitic stainless steel, two static tests were adopted: the tensile-shear and the cross-tension tests, as shown in Figure 5.

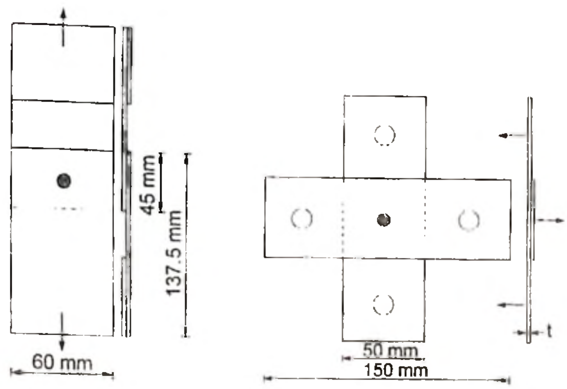

Figure 5. Tensile-shear (left) and cross-tension (right) tests for spot-welded specimens.

4.2 Weld test results and discussion

In general, almost all stainless steel specimens (both spot-welded and laser-welded) failed across the weld for the tensile-shear test, whereas the carbon steel specimen failed in the heat-affected zone of the material. By contrast, for the cross-tension tests all the stainless steel specimens failed by pulling a plug of material from the opposite sheet. This suggested that the welds were of sufficient quality but that the stainless steel welds were rather weak when subjected to shear loading. However, it was found that increasing the size of the weld nugget from $5\sqrt{t}$ to $8–12\sqrt{t}$ altered the failure mode from the weld to the heat-affected zone even in the least ductile (HT) condition. It can, therefore, be assumed that the softening which occurs at the weld nugget during welding can be circumvented through appropriate resizing of the weld nugget. On the basis of equal weld area, the laser-welded specimens failed at marginally higher loads than the spot-welded joints.

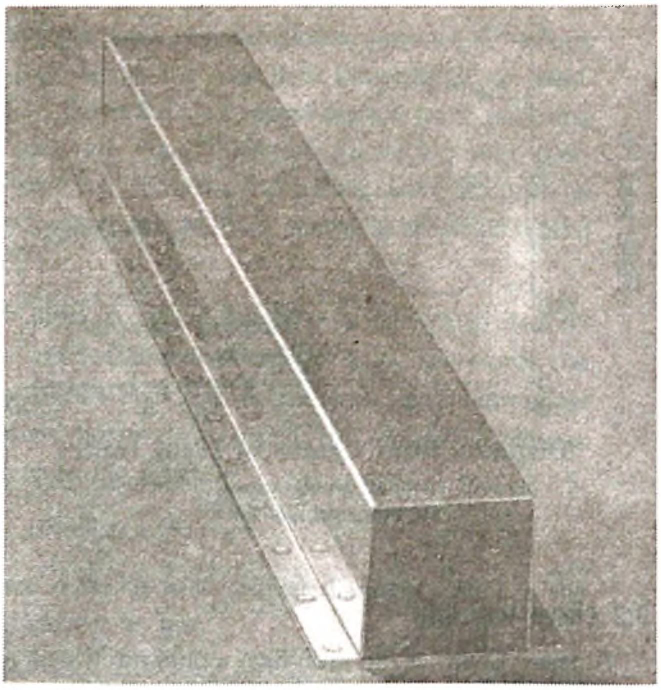

Figure 6. Specimen design (60 mm × 60 mm section; flange width 15 mm, length 500 mm and spot-weld spacing 40 mm).

5. IMPACT BEHAVIOUR OF STRUCTURAL SECTIONS

Structural sections were fabricated to investigate the behaviour of spot-welds and laser-welds subject to more realistic loading conditions. Fay and Suthurst (1990) note that such small-scale structures 'fit into the testing regime between small laboratory specimens and complete structures and can be tested ... under a variety of loading conditions'.

5.1 Specimen Design

To date, there does not appear to be a standard small-scale structural design and different organisations have instead developed 'in-house' specimens. The section shown in Figure 6 was designed to accommodate the diameter-to-thickness ratio required to avoid Euler buckling, account for the testing machine capacity and to maximise the use of material.

5.2 Welding Procedure

Spot-welded specimens were initially prepared using standard ($5\sqrt{t}$) size weld nugget diameters using a weld spacing of 40 mm. Laser-welded specimens were prepared using stitch welds, with an equivalent weld area to the spot-welded structures. In addition, a series of continuously welded specimens were tested as a comparison with the stitch configuration.

5.3 Testing Method

Quasi-static testing was carried using a Denison 500 kN capacity hydraulic testing machine. Impact testing was undertaken using a 10 tonne drop test rig. However, the velocity was restricted to 4.4 m/s to ensure that the energy absorption of the specimen was not exceeded. The impact load was recorded using a 500 kN load cell which was logged at 500 kHz. Displacement was measured using a line-scan camera, mounted directly in front of the specimen.

5.4 Structural test results and discussion

Under quasi-static testing, the structural sections tested typically failed by progressive folding with the base plate forming an integral part of the structure, as shown in Figure 7. However, the highly cold-worked material (301L HT) did not possess sufficient ductility to accommodate the large plastic strains required to form the folds observed in Figure 7. Instead, extensive tearing was observed along the fold lines produced during fabrication, causing catastrophic, rather than controlled, collapse behaviour as shown in Figure 8.

A salient finding was that the structures suffered few, if any, weld failures during defomation, suggesting that under such loading, the standard size nugget diameters are sufficient, negating the need for the larger nugget diameters considered earlier. Furthermore, as shown in Figure 7, the welds appear to dictate the formation of the folds thus affecting the energy absorption performance.

Figure 7. Specimen subjected to quasi-static axial load

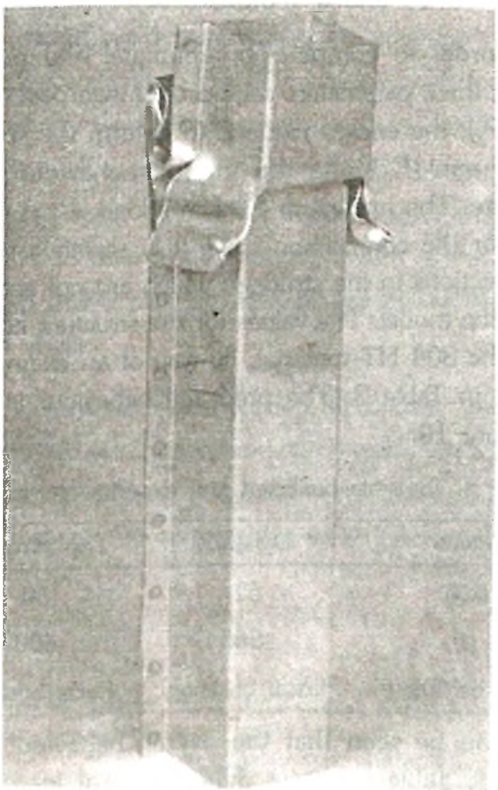

Figure 8. Catastrophic collapse behaviour

Under dynamic loading, the post-buckling behaviour was found to be similar to that observed under quasi-static testing. Progressive folding (albeit at a faster rate) was observed for all of the specimens with the exception of the 301L HT condition which, once again, suffered catastrophic failure due to tearing at the fold lines produced during fabrication. Peak (buckling) loads were observed to be significantly higher than those observed under quasi-static loading (between 20% and 80% for the range of stainless steels and 100% for the carbon steel); however, the mean loads and hence energy absorption, were found to be remarkably similar (within 10% for the range of stainless steels and 26% for the carbon steel).

In order to compare the energy absorption performance of the specimens, the 'energy required to deform the specimen by 10 mm', E1O' was employed:

$$E_{10} = \frac{E}{S} \times 0.01\text{m} \qquad (2)$$

where E is the total energy absorbed over the crush distance, s.

This is shown in Figure 9 for spot-welded structures with the range of materials ranked in order of increasing proof strength. In general, increasing parent material strength leads to improved energy absorption performance, however, a limit clearly exists as to the extent to which the parent material can be cold-worked before the loss of ductility significantly affects the energy absorption performance. Little difference was observed between spot-welded and stitch laser-welded structural sections, although the stitch welds were found to be less efficient in dictating the fold formation than the spot-welds.

A number of specimens were prepared using 20, 80 and 120 mm spacing to compare with the 40 mm spacing used previously and tested under quasistatic conditions. It was observed that at larger spacing, the backing plate ceased to remain an integral part of the structure and either collapsed in a stable mode out of phase with the main channel or separated completely.

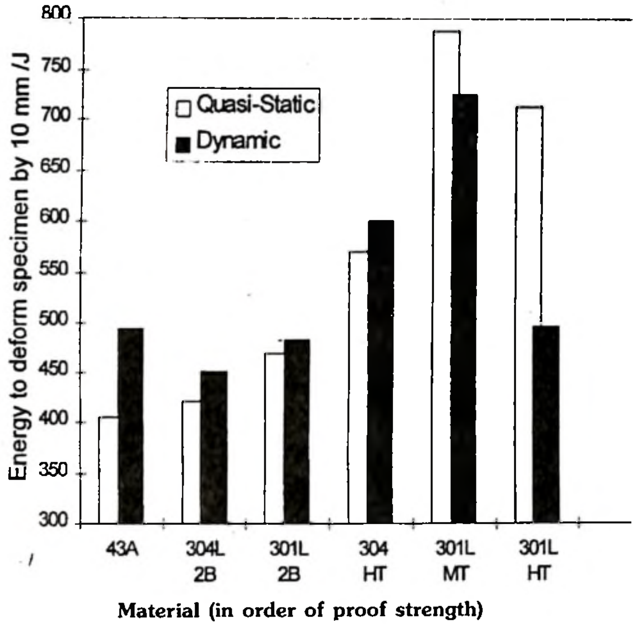

Figure 9. Energy required to deform specimens by 10 mm.

Clearly, the weld spacing is an important issue and affects the general behaviour of the structure as well as dictating the formation of folds during deformation.

6. NON-LINEAR FINITE ELEMENT MODELLING

Oasys LS-Dyna3D [Oasys Ltd. (1995)], a dynamic, non-linear finite element package was used to examine the extent to which the post-buckling deformation of spot-welded structures could be successfully modelled.

6.1 Validation of Dyna3D

The model was constructed using 4 node quadrilateral shell elements to represent the sheet metal (2356 nodes and 2200 shell elements). The material model was created using results obtained from tensile testing. Two stonewalls, one of which was given a velocity of 4.4 m/s were used to represent the dropmass and impactor respectively. The spot-welded joints were modelled using the Constrained-Spotweld function in version 6.0 of Dyna3D which links two nodes with a massless rigid beam. Values from the static tests reported above using standard size nugget diameters were used to provide data for the shear and normal failure forces required for use in the combined loading failure mode equation:

$$\left[\frac{\max(f_n,0)}{S_n}\right]^n + \left[\frac{|f_s|}{S_s}\right]^m \geq 1 \qquad (3)$$

where f_n and f_s are the normal and shear interface forces; S_s and S_n are the normal and shear force at failure. n and m are the normal and shear force exponents.

Strain-rate sensitivity is incorporated into the material model using the Cowper-Symonds constitutive equation:

where σ'_y is the yield stress at strain-rate $\dot{\varepsilon}$, σ_y' is the yield stress under static loading and D and q are material constants required for the material model.

$$\sigma'_y = \sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{1/q}\right] \qquad (4)$$

Suitable strain-rate parameters for austenitic stainless steel appear to be the subject of some debate in the literature. However, for this validation exercise the strain-rate parameters obtained by interpreting the data presented by Davies and Magee (1975) were used (D = 8.5E+04 and q = 3.55).

In order to compare experimental and predicted results, three parameters were used: mean post-buckling load (P_m), the energy required to deform the specimen by 10 mm (E_{10}) and the 'overall behaviour' of the structure. The maximum (buckling) load, P_{max}, was not used for the comparison since it is sensitive to initial imperfections in the structure which are not accounted for in the model. The values for the structure fabricated from the 304 HT material, by way of an example, are shown in Table 3. The predicted behaviour is shown in Figure 10.

Table 3. Dynamic predicted and experimental results

Parameter	Dyna3D	Experimental
P_m (kN)	57	59
E_{10} (J)	565	600
Overall behaviour	Local buckling	Local buckling

It can be seen that the overall behaviour of the structure subjected to a dynamic axial load is well represented with mean post-buckling load and, consequently, the energy required to deform the specimen by 10 mm predicted to within 10% of the experimental values.

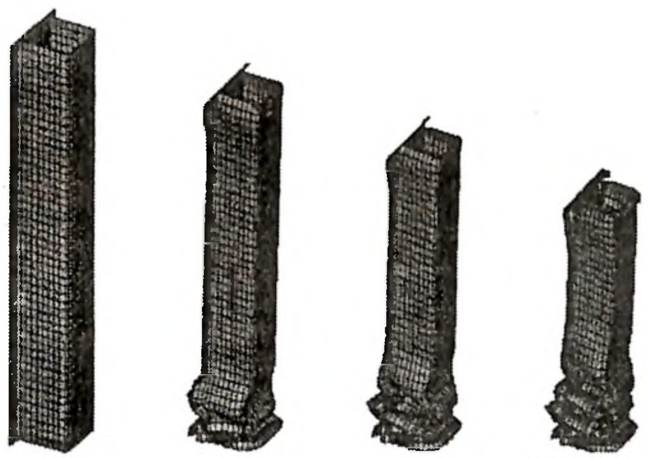

Figure 10. Predicted axial deformation of spot-welded structures subjected to dynamic loading (304 HT) (left to right: t=0, t=0.015, t=0.03, t=0.045 s).

7. CONCLUSIONS

Static tests using single spot-welds prepared using recommended weld parameters to produce nugget diameters according to the 5Öt criteria were found to fail across the weld interface during shear loading but in the heat-affected-zone of the weld during normal loading. However, the use of larger nugget diameters was found to alter the mode of failure under shear loading so that a plug of material was pulled from the opposite sheet.

Spot-welded and laser-welded structures, prepared using standard size nugget and stitch welds were shown to perform satisfactorily under both quasi-static and impact loading. Although minor weld failure occurred, this did not appear to affect the overall collapse behaviour which, provided the parent material possessed sufficient ductility, was dominated by progressive folding, absorbing significant amounts of energy.

Weld spacing was shown to be an important parameter: increasing the distance between welds was found to alter the collapse mode such that the backing-plate ceased to remain an integral part of the structure.

With appropriate choice of parent material condition, structural design and weld spacing, there-fore, stainless steel structures may be used to absorb significant levels of energy in a controlled manner as required in the event of an impact.

It was also shown that the post-buckling behaviour of spot-welded structural sections could be modelled with reasonable accuracy using Dyna3D. Predicted energy absorption values, were found to be within 10% of those observed experimentally.

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The authors wish to express their thanks to the BR board, the Nickel Development Institute and also to the material suppliers.

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