LIGHTWEIGHT DESIGN THROUGH OPTIMISED JOINING TECHNOLOGY

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ABSTRACT

Starting with the requirements a structure has to meet, it was shown how joining technology can contribute towards meeting these requirements and the interdependency between joining technology, material and structural design was highlighted. With the help of examples, it was illustrated how improvements of the particular joining technology, design optimisation, use of superior materials in conjunction with a suitable joining technology, and the use of hybrid joining technologies can contribute towards improving the properties of a structure and thus achieve weight savings.

IIW-Thesaurus keywords: *Design; Structures; Mechanical properties; Welded joints; Spot welds; Weld bonding; Nonwelded joints; Rivets; Process selection; Combined processes; Optimisation; Selection; Steels; Aluminium alloys; Load carrying; Weight; Loading; Comparisons; Fatigue strength; Elongation; Influencing factors; Thickness; Shear loading; Shear strength; Shape; Yield strength; Practical investigations.*

1 INTRODUCTION

Lightweight design implies the most effective use of materials. An essential prerequisite for the effective and intelligent use of materials is a comprehensive knowledge regarding their physical and technological properties, the forces in the structure under service conditions, with respect to their magnitude, direction, spatial and transient distribution, the load-carrying ability of the joints as well as information regarding suitable manufacturing technologies, etc.

An optimally designed structure must fulfil all requirements with a minimum of effort. This means, among other things, that the structure must be provided with the required properties, e.g. stiffness, fatigue strength, behaviour under static and impact loading as well as corrosion resistance, as economically as possible.

Joining technology has a decisive influence on the design of any structure. Together with the material and the design, it is responsible for the mechanical properties of a structure. All three parameters are interdependent, so that a balanced global approach is necessary when designing a structure with optimal properties.

The selected joining technology influences the materials that can be used, their cross-sections, the properties of the joints, and through them, the design of the structure and its weight.

Lightweight design, as a subject, has many facets. A global consideration would prevent focussing on important, relevant aspects. Therefore, in the following, the emphasis will be laid on automobile design in general and the body-in-white in particular.

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2 DETERMINING THE LOAD-CARRYING PROPERTIES OF JOINTS

In order to design a structure using engineering formulae, it is necessary to have precise knowledge about the load-carrying properties of the relevant joints as a function of the material and sheet thickness combinations, the types of stresses, their magnitudes, the local direction-dependent stiffness of the structure at the locations of the joints, corrosion and environmental aspects, service temperatures, temperature shock, etc.

In spite of intensive research in recent years, there are still very little relevant data available for thin-walled structures as used in the automobile industry. Thereby, it is of decisive importance to know, which joint properties are of significance for the function and service life of a vehicle, and how these can be assessed with the aid of tests.

To begin with, one must consider which types of loads the joints can be subjected to and which of these are relevant for structures. In the case of spot welds or punctiform joints, for example, pure torsion and pure cross-tension can be neglected since these are extremely seldom in structures. As shown in Fig. 1, two types of shear loads and peel or one-sided cross-tension loads are the three basic types of loads, which joints can be subjected to in structures. In certain cases, punctiform joints can be subjected to torsion together with shear and cross tension loads, e.g. in 3-sheet joints when the flanges are recessed. The influence of this type of load

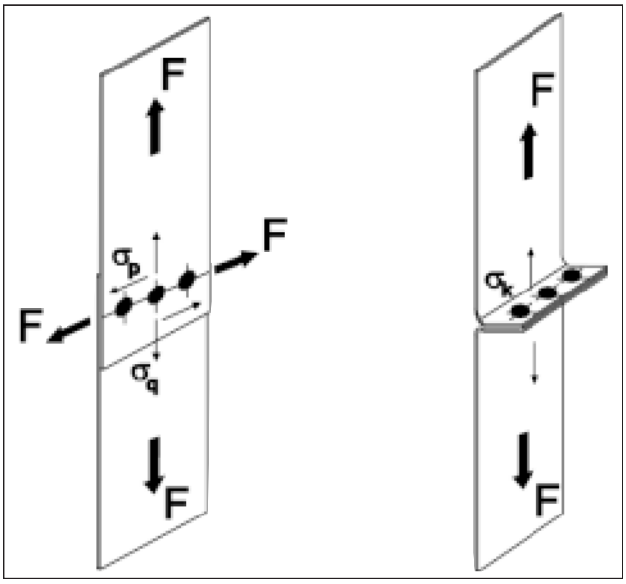


Fig. 1. The three basic types of loads that joints can be subjected to.

on the fatigue life, however, is limited since its proportion is generally very small. Furthermore, especially in the case of mechanical joints, this type of load must be avoided through design measures. Therefore, this case will not be dealt with further in this paper.

In the case of true-to-life thin-walled structures, it can generally be assumed that joints are never subjected to any of the above-mentioned types of loads, either singly or in a pure form. In the case of lap joints, at least one type of shear load and, due to the local deformation of the sheets caused by it, peel stress is present.

Even if the primary load in a lap joint is pure shear, a peel stress component will be generated, whose magnitude depends on the size of the deformation caused by the shear load in the joint. This deformation is a function of the bending moment, which depends on the sheet thicknesses involved, the magnitudes of the acting forces and the local stiffness. The stiffness itself is a function of Young's modulus of the materials and the local geometry, e.g. sheet thicknesses, flange width, overlap, location of the joint on the flange, bending radii etc.

The necessity for differentiating between the two types of shear stresses lies in the fact that despite identical nominal loading, the fatigue lives of joints subjected to the two types of shear loads can be quite different. This is due to the different direction-dependent local stiffnesses in the joint area, which lead to different local deformations and thus different types and magnitudes of stresses, especially peel stresses.

In order to generate the data required for design purposes, it is imperative that suitable specimens and test procedures, and last but not least, suitable testing devices are used. If the required data cannot be generated using standard tests, then suitable new tests, jigs and procedures must be developed. Through the development of suitable specimens and testing jigs, it is possible to generate the required data for the relevant material and thickness combinations, joining technologies etc., Figs. 2a and 2b. [1]

In principle, the generated results have a general validity. However, due to the varying differences in local stiffnesses, an adaptation for the structure being considered is, in most cases, necessary. These differences in stiffnesses influence the local deformations, and through them, the types, proportions and magnitudes of the stresses.

3 WAYS AND MEANS OF REALISING LIGHTWEIGHT STRUCTURES

Joining technology can play a decisive role in reducing the weight of a structure. Since, as mentioned above, joining technology, materials and structural design are interdependent parameters, an isolated consideration is not appropriate. Therefore, the contributions of the following measures towards achieving lightweight structures will be considered jointly:

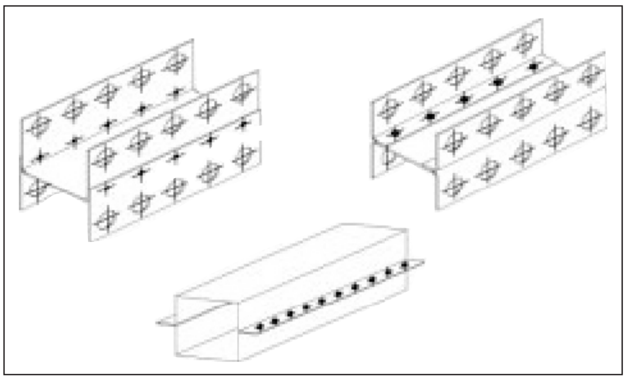
a) Optimisation of the joining technology;

b) Optimisation of the design;

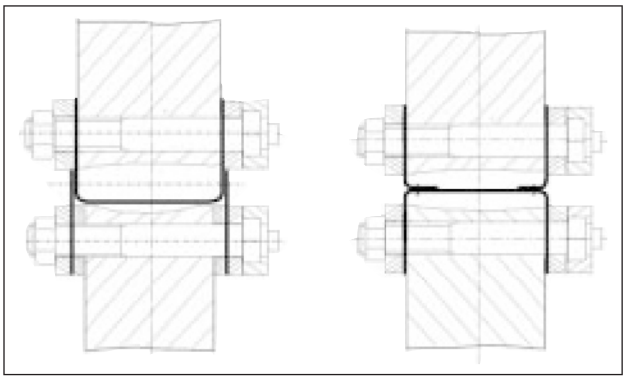
c) Use of suitable materials and;

d) Use of hybrid joining technologies.

From a rational point of view, a pre-requisite for the practical application of any of the above measures, in the design phase, is knowledge regarding their quantitative



(2a)



(2b)

Fig. 2. Specimens suitable for generating the different types of stresses (2a) and H-specimens clamped in testing jigs (2b).

effects. Their use in a structure, however, does not mean that consequent conformance tests can be dispensed with, but a substantial reduction in the amount of effort required for experimental tests can be achieved.

A calculation of the fatigue life of a structure, using the so-called engineering method, requires the availability of quantitative data for the load-carrying properties of the joints. This data must be available for the boundary conditions relevant to the structure under consideration, e.g. material and sheet-thickness combination(s), joining technology, magnitude and direction of loads, design-dependent local stiffness etc.

3.1 Optimising joining technology

The properties of the joints can be improved by optimising the joining technology, so that structures, in which the technology is employed, show improved relevant properties. Should an increased stiffness or a longer fatigue life not be necessary, then at least a part of the improvements can, for example, be used for reducing wall thicknesses and thus for reducing weight.

Fig. 3a represents a macro-section of a self-piercing riveted (SPR) joint, showing the state of the art about 1982. The cutting-through of the die-side sheet, the squashing and buckling of the shank, the small degree of flare and the hollow spaces under the rivet head are negative points. As a result, this joint showed relatively low shear and peel strengths, an unsatisfactory fatigue life and poor corrosion resistance.

Fig. 3b shows a macro-section of an improved joint. In order to facilitate the production of a large number of prototype rivets with different geometries and the handling, these tests were carried out using 2:1 scale turned rivets. For the same reason, 2mm Al99.9w sheet was used as material for the test specimens. Modifications were made to the geometries of the rivet, the die and the clamping. The improvement to the geometry of the joint is obvious. The flaring of the rivet is almost optimal as also the undercut. The shear strength of the joint could be increased by approx. 40% and the peel strength by approx. 25%. Furthermore, the area under the force vs. elongation curve – a measure for the energy absorption properties of the joint – was almost five times larger, a result due, among other factors, to the increased undercut. In addition, the foot-end of the rivet is completely covered by a fairly thick layer of sheet metal and there are no gaps under the head of the rivet, Figs. 3b and 4. Although no fatigue tests were carried out with these joints, but because of the higher static strength and the higher compressive stresses generated by the flaring of the rivet shank, a noticeable improvement in fatigue performance, including a flatter slope of the Woehler curve can be expected.

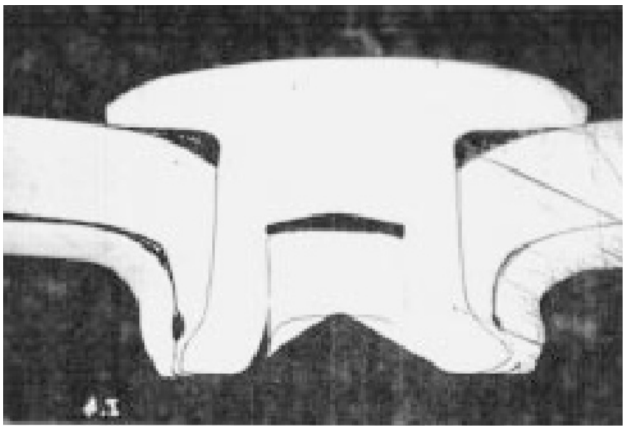
Clinching is a press-joining technology with which lap joints are made by locally cutting and/or deep-drawing sheet metal into the die, and then flattening this material between punch and anvil. The resulting joint is shape and force actuated.

Fig. 5a shows a macro-section of a clinched joint made using commercially available tools. The critical points of clinched joints are the wall thickness of the punch-side sheet in the “neck” of the joint and the undercut. With commercial tooling, the wall-thickness in the neck is normally 25 to 33% of the nominal sheet thickness. The depth of the punch stroke must be increased to improve undercut. This, however, stretches the material and decreases the wall thickness in the neck zone.

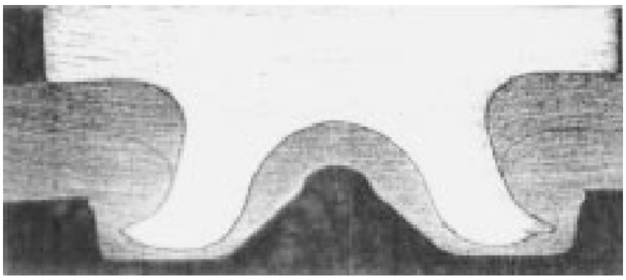
Through modifications of the punch and die geometries, the wall thickness in the neck zone could be increased from about 25% to about 55% of the nominal sheet thickness, Fig. 5b. The improvement in shear strength was ~35%, and the corresponding improvement in peel strength ~25%, Fig. 6. Here too, corresponding gains in energy absorption behaviour and fatigue strength can be expected.

3.2 Optimisation of the design

The optimisation of the structure can be carried out with different aims, each of which may be given a different priority. If lightweight design is the primary goal, then, keeping the priorities in mind – stiffness, fatigue strength, etc. – the materials employed must be put to use as effectively as possible. Thereby, as stated above, join-



(3a)



(3b)

Fig. 3. Self-piercing riveted joint – state of the art 1982 (3a) and improved joint achieved through modifications to rivet geometry, die and clamping (3b).

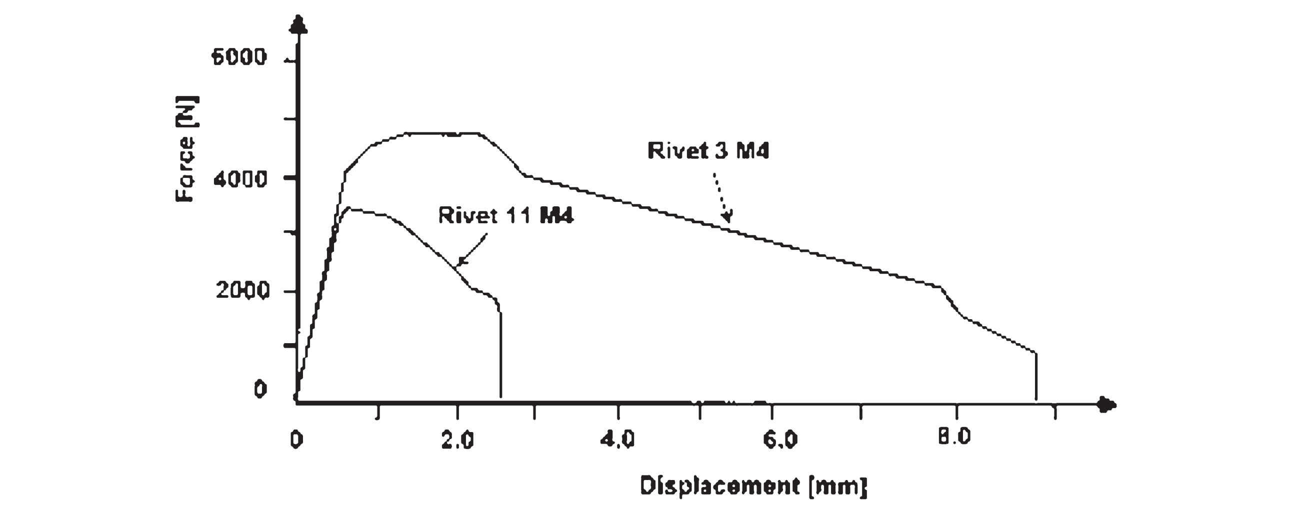
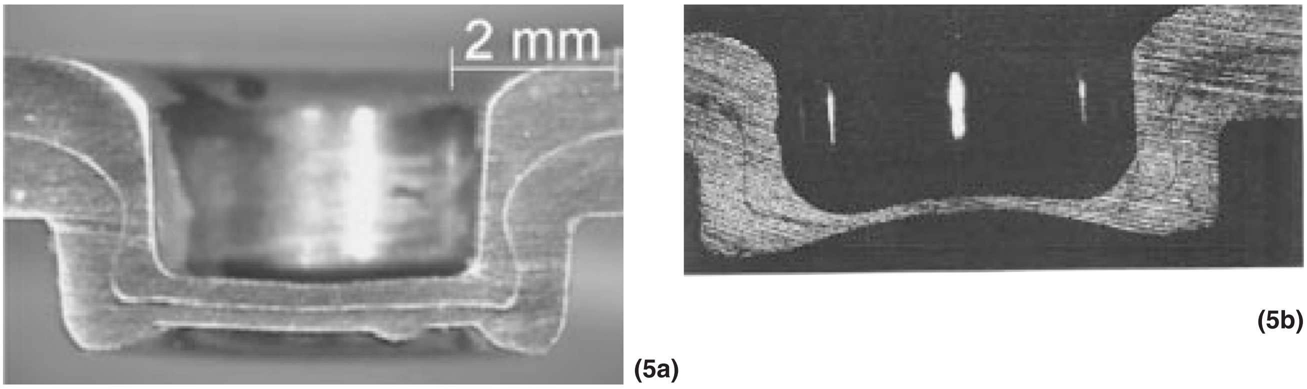


Fig. 4. Force vs. elongation curves for standard and improved self-piercing riveted joints.



(5a) (5b)

Fig. 5. Geometry of clinched joints: (5a) using standard tools and (5b) using modified tools.

ing technology can play a very important part, because it can influence the:

– Stiffness (in the case of tension, compression, torsion and bending);

– Fatigue behaviour (under constant and random amplitude loading);

– Energy absorption behaviour (Crash behaviour, safety aspects);

– Materials to be employed, their thickness and material combinations (metallic, non-metallic, combinations, coatings);

– Spatial requirements (bending moment and torsional moment of inertia of closed cross-sections, flange widths).

Furthermore, depending on the joining technology selected, the geometry of the joints, e.g. lap joint, butt

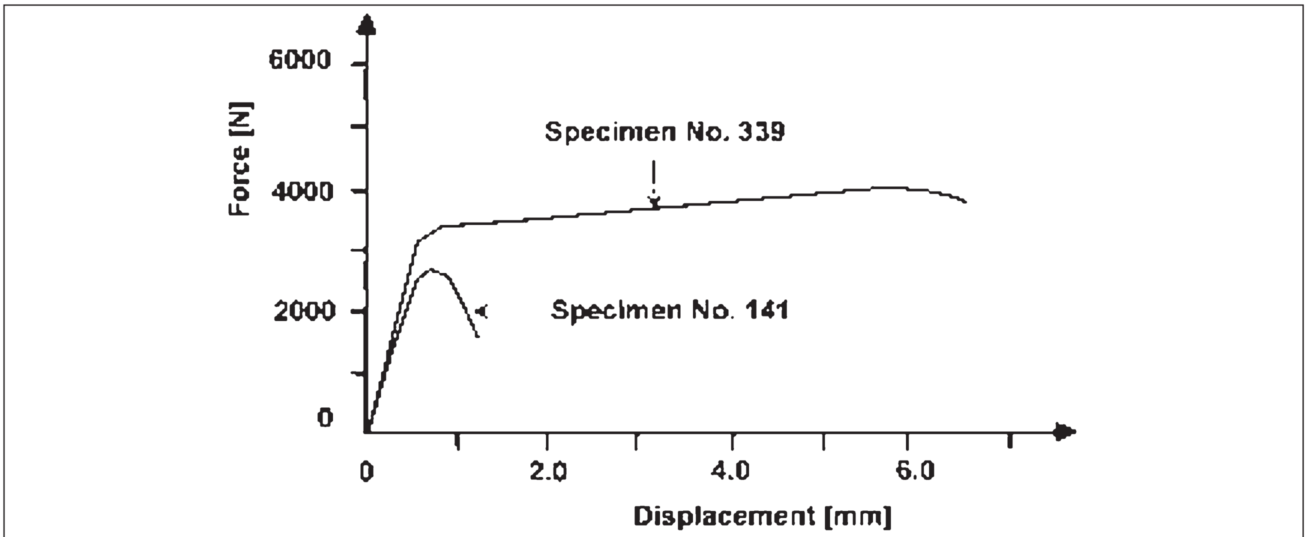


Fig. 6. Force vs. elongation diagrams of clinched joints made using standard and modified tools.

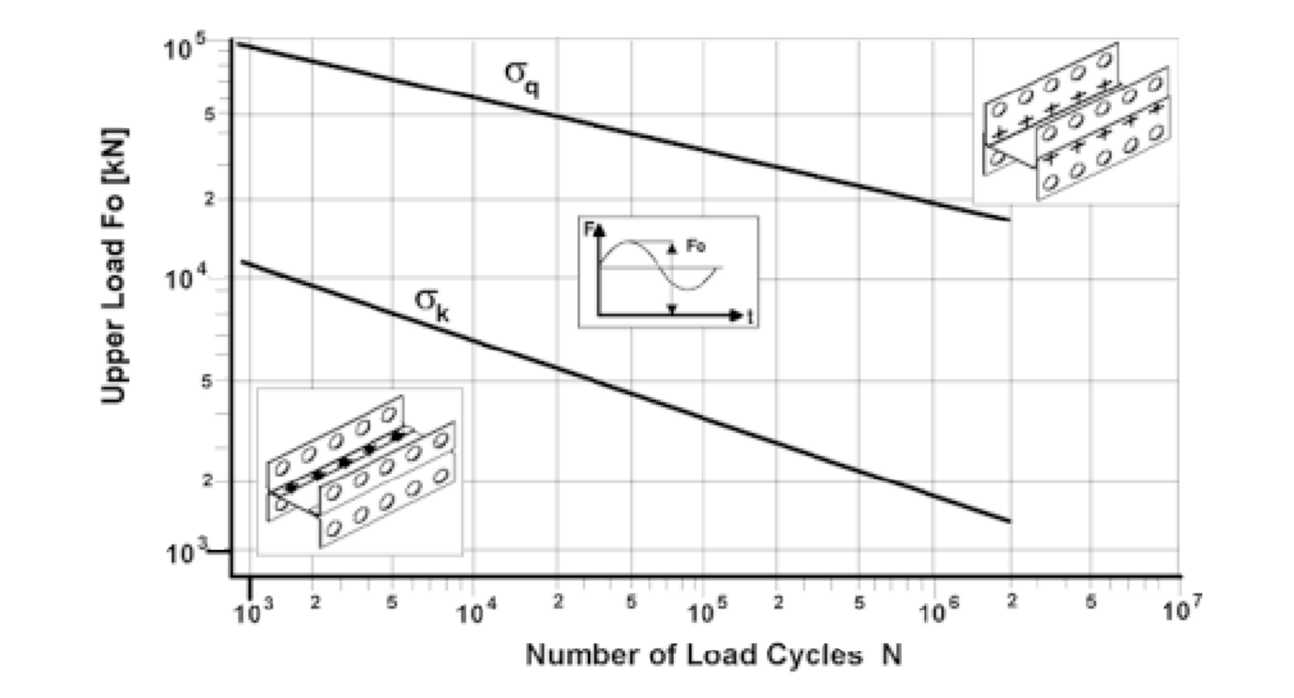


Fig. 7. Woehler curves of spot-welded H-specimens in 1 mm DC 04 steel sheet subjected to shear and peel loading.

joint, T-joint, etc. and their mechanical properties will have a direct influence on the properties of the structure and its geometry.

Fig. 7 shows the results of fatigue tests with spot welded specimens made from 1mm DC 04 steel sheet in which the welds were subjected to shear and peel loads. The ratio of the permissible loads is approx. 10. The difference in fatigue life is ~10^4, i.e. a spot weld subjected to a cyclic shear load transverse to the joint line will have a fatigue life ~10,000 times greater than an identical spot weld subjected to a peel load of the same amplitude. The ratio of the corresponding static loads normally lies between 1: 2.5 and 1: 4.

Basically, the same trend is observed for joints made with different technologies, although the absolute ratios and values may differ due to differences in material properties, joint geometry dependent notch factors, residual stress state etc.

The influence of the R-value on the fatigue life of H-shear specimens is to be seen in Fig. 8. As is to be expected, the fatigue behaviour under alternating cyclic loading is better than that under pulsating load. The large difference in fatigue life ~10^2 , however, was not expected.

This result, however, confirms the negative influence of peel loading, since with the increase in the load ampli-

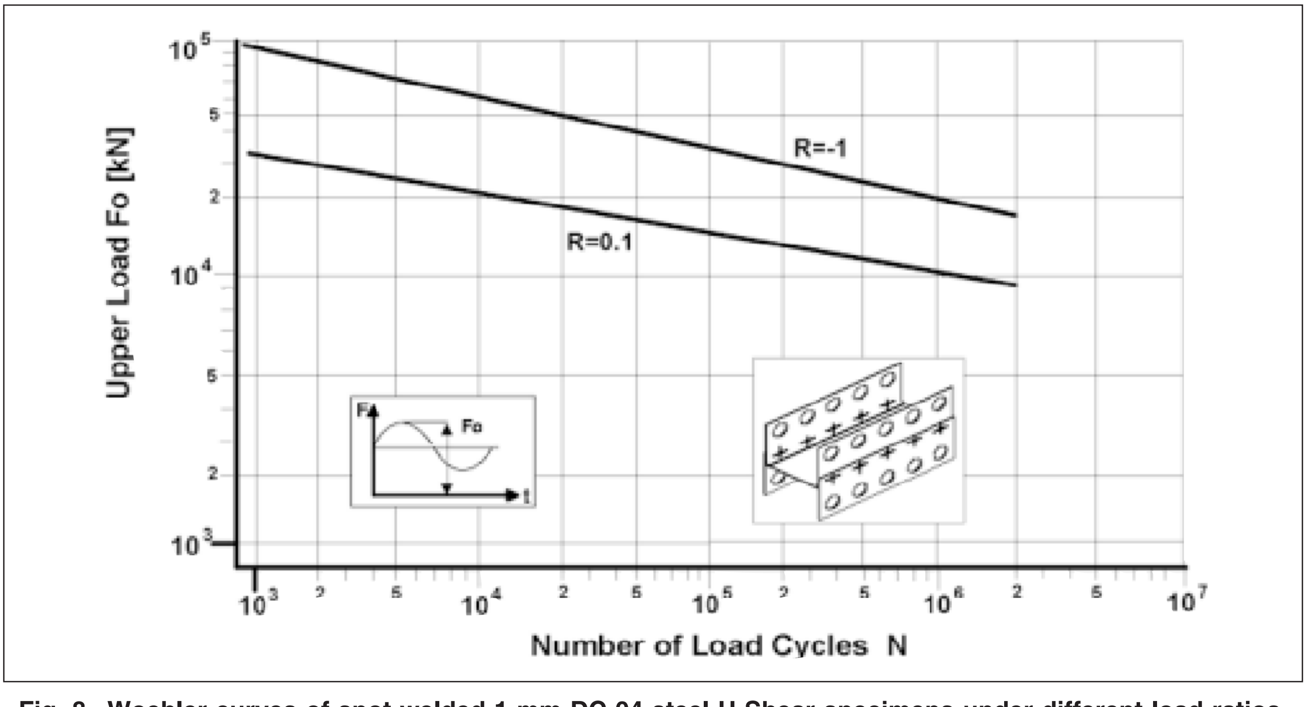


Fig. 8. Woehler curves of spot-welded 1 mm DC 04 steel H-Shear specimens under different load ratios.

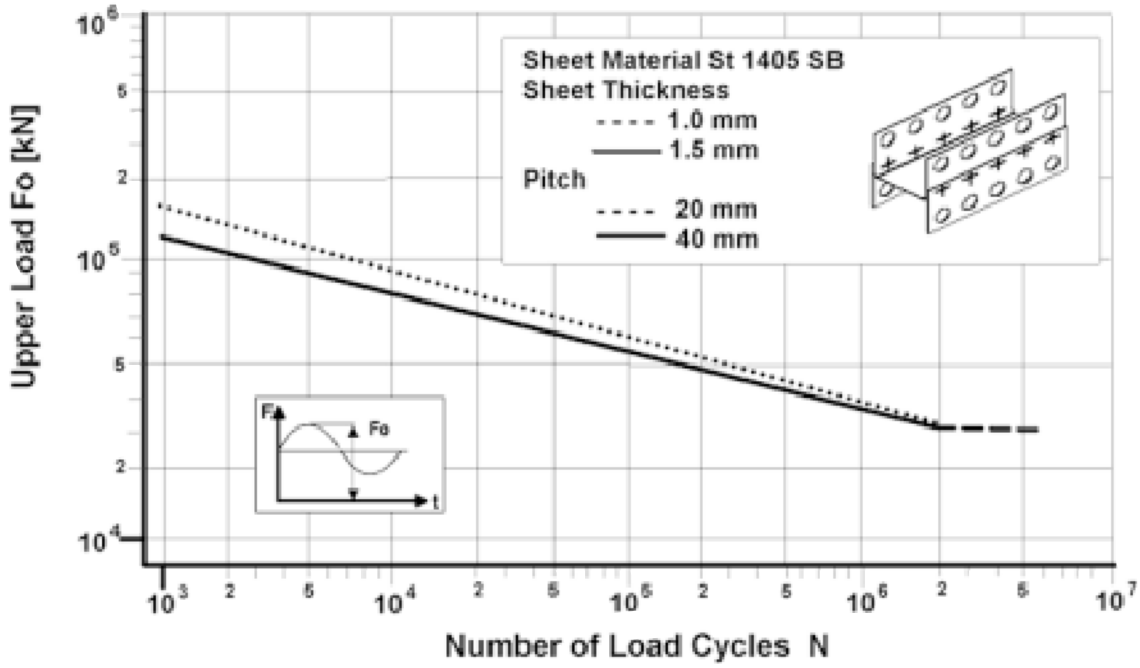


Fig. 9. Influence of sheet thickness and pitch on the fatigue life of shear loaded H-specimens.

tude, the ratio of the cross-tension component increases disproportionally. The greater slope of the Woehler curve is another indication of the negative influence of this type of loading.

3.3 Effect of sheet thickness, material and pitch

An increase in sheet thickness and/or the use of a superior material can, when used intelligently, improve the stiffness and the fatigue performance of a structure. In the case of spot welds subjected to shear loads, as in the H-shear specimen in Fig. 2a, the superior material should be used for the U-shaped member, as it is the weak point in this case. Similarly, the material with the superior properties should, in the case of H-peel specimens, be used for the L-shaped members.

A decrease in sheet thickness does not automatically mean a loss in stiffness or poorer fatigue life. The results of fatigue tests in Figs 9 and 10 show clearly that, e.g. by decreasing the pitch of the welds from 40 to 20 mm, the fatigue performance of both shear and peel H-specimens could be improved, even though the sheet thickness was reduced from 1.5mm to 1.0mm, a weight saving of 33.3%! The stiffness too was improved.

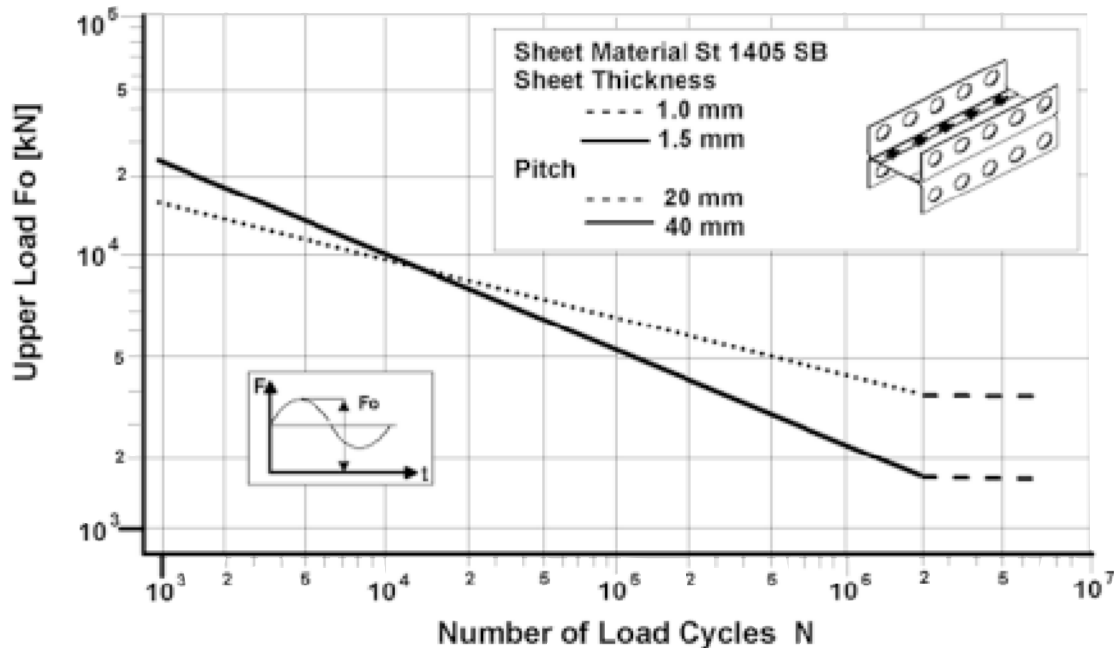


Fig. 10. Influence of sheet thickness and pitch on the fatigue life of peel loaded H-specimens.

In most cases, the use of conventional high strength steels in conjunction with spot welding as the joining technology, does not lead to the expected general improvement of the relevant mechanical properties of the joints under quasi-static or cyclic loading, Fig. 11 [2, 3, 4]. This is due to the detrimental effects of the heat input during the welding process. In some cases, a substantial deterioration of the properties has to be

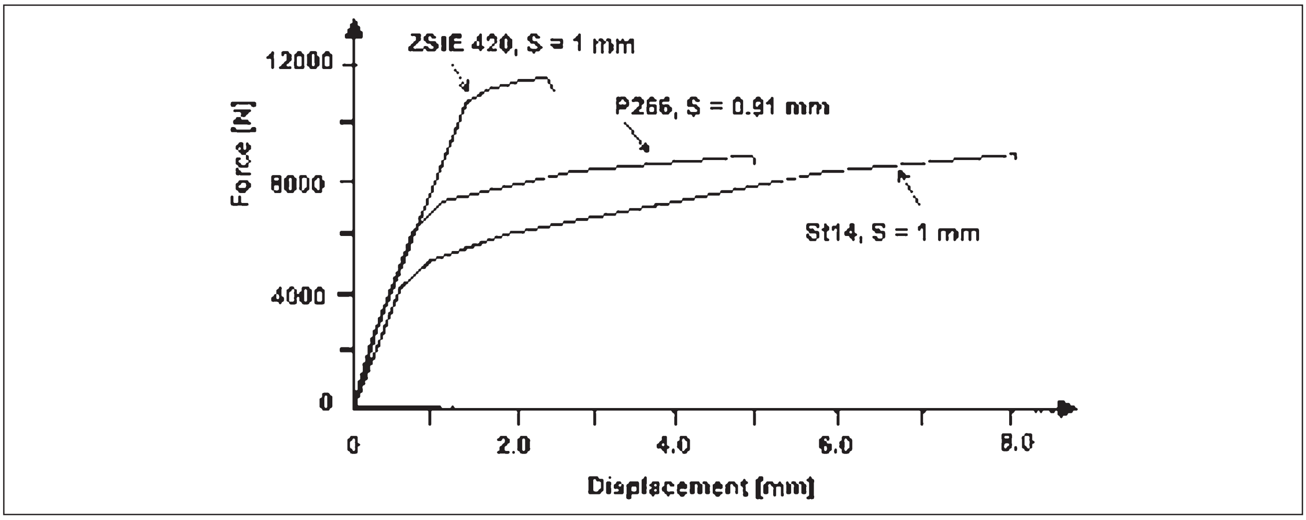


Fig. 11a. Force vs. elongation diagrams of standard spot-welded specimens of different steels under quasi-static shear-tension load [2].

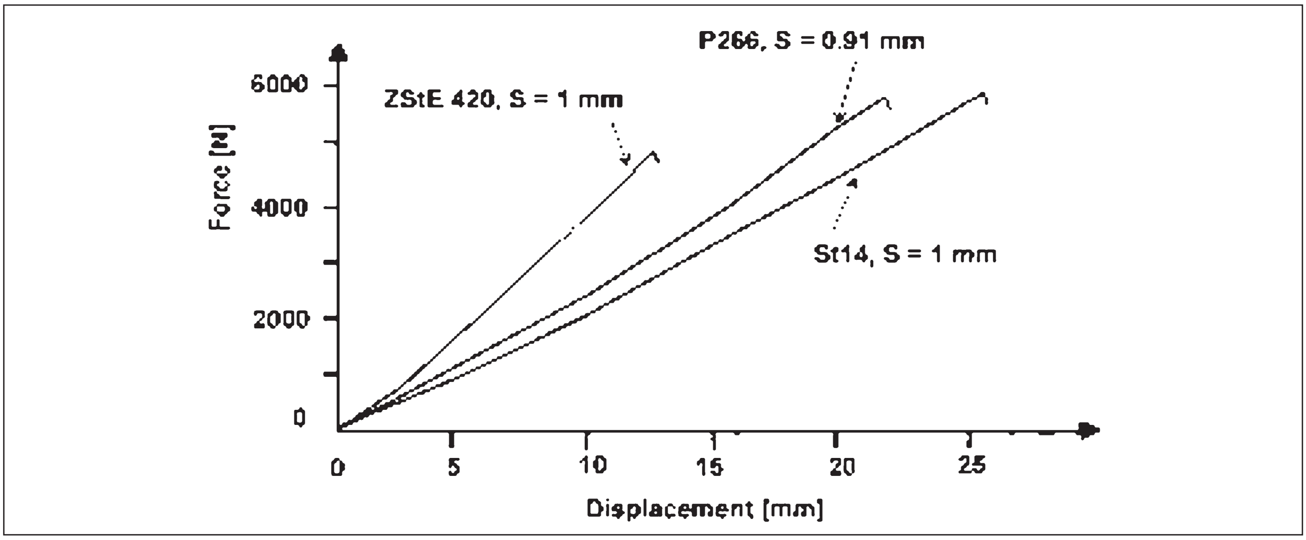


Fig. 11b. Force vs. elongation diagrams of standard spot-welded specimens of different steels under quasi-static cross-tension load [2].

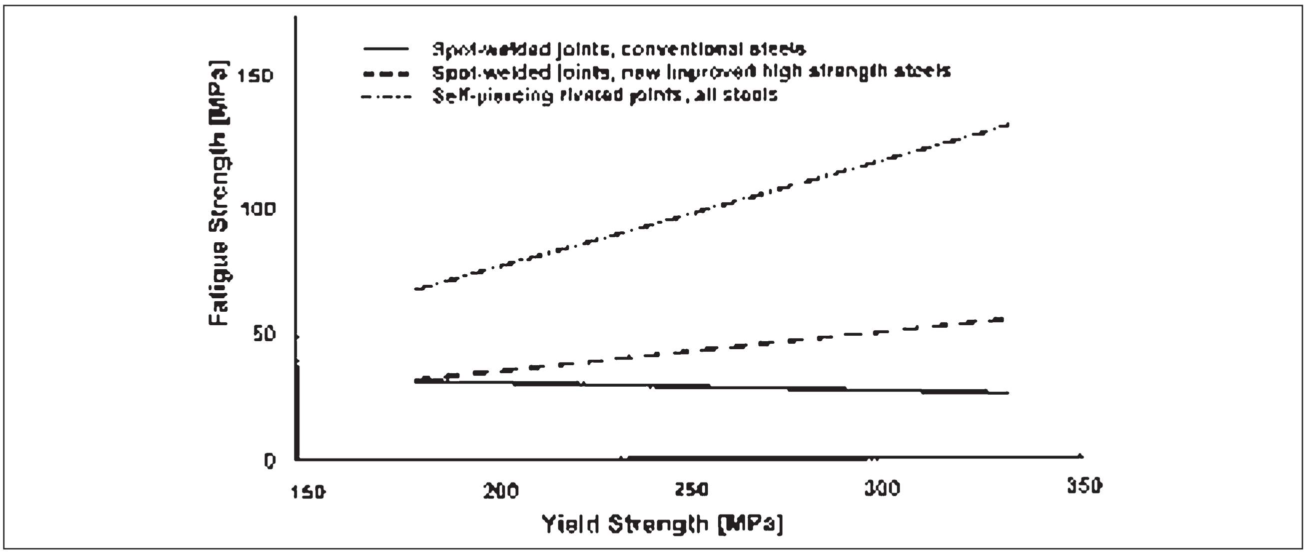


Fig. 11c. Influence of the technical yield strength of steel sheet on the fatigue strength of spot-welded and self-piercing riveted joints, (modified from [3]).

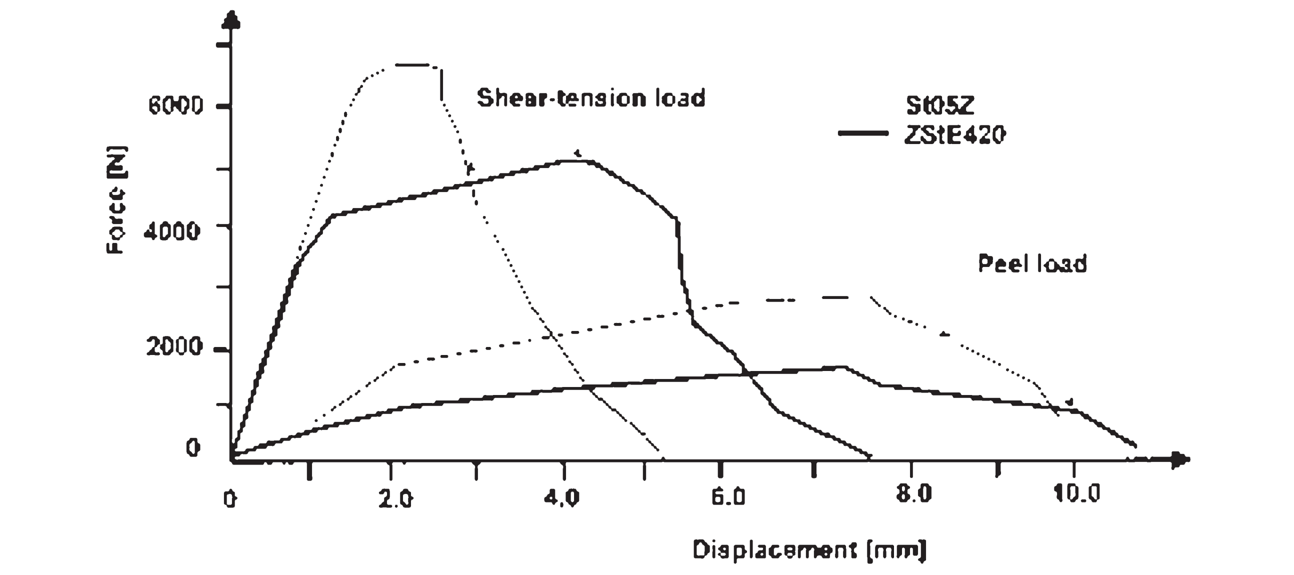


Fig. 11d. Force vs. elongation diagrams of standard self-piercing riveted specimens of St05Z and ZStE 420 1mm sheet under shear-tension load and peel load [4].

accepted. Due to the increase in hardness and the corresponding increase in the strength of the material in the weld zone, often higher strengths are registered under quasi-static loads. Even in the case of newer improved high strength steels, there is mostly only a marginal improvement in the fatigue properties of spot-welded joints, Fig. 11c [3]. In the case of self-piercing riveted joints, however, there is, in most cases, a noticeable improvement under quasi-static and cyclic loading as well as in the energy absorption behaviour of the joints, Figs. 11c and 11d. [3, 4].

3.4 Improvements through the use of hybrid joining technologies

Fig. 12 shows the results of tensile shear tests of spot welded and weld bonded joints in aluminium sheet, using different adhesives. The force vs. elongation curves show clearly the vast superiority of the weld bonded joints, especially with the newer toughened adhesives. Particularly to be noted is the very large increase in energy absorption, a property of vital importance for crash behaviour.

Fatigue tests were carried out with H-shear specimens made with different joining technologies. The results in Fig. 13 show that the specimens made with the hybrid joining technology have by far the best fatigue performance.

4 SUMMARY AND CONCLUSIONS

Starting with the demands a structure has to fulfil, it was shown that the realisation of lightweight structures

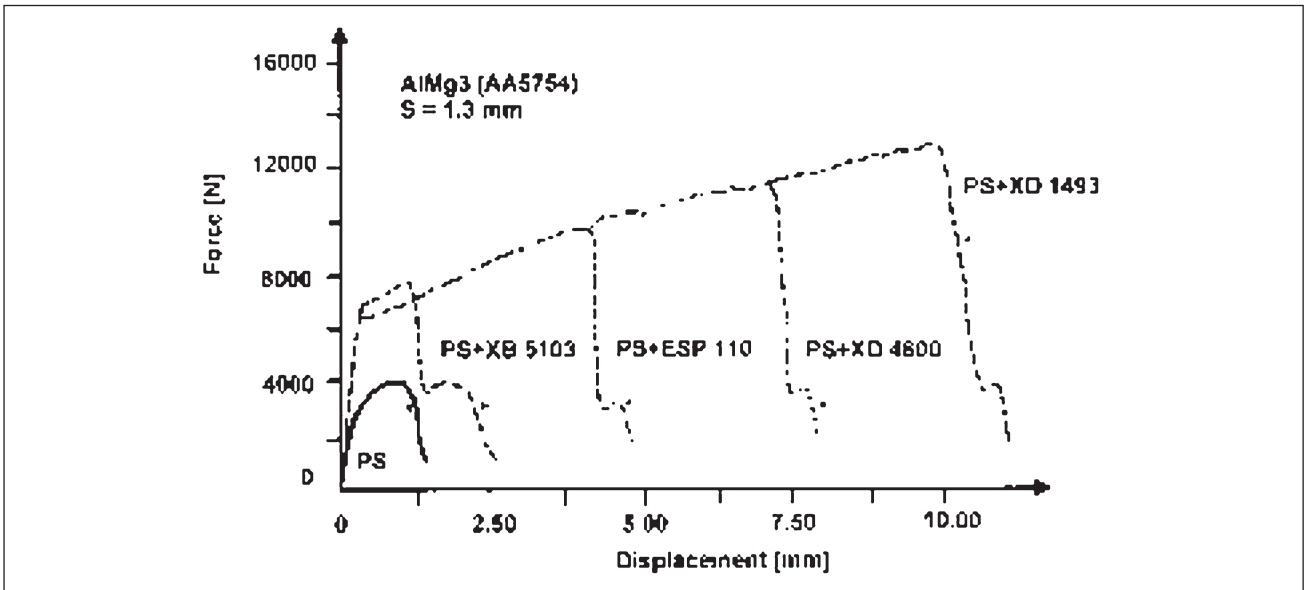


Fig. 12. Force vs. elongation curves for spot welded and weld bonded tensile shear specimens made using different adhesives.

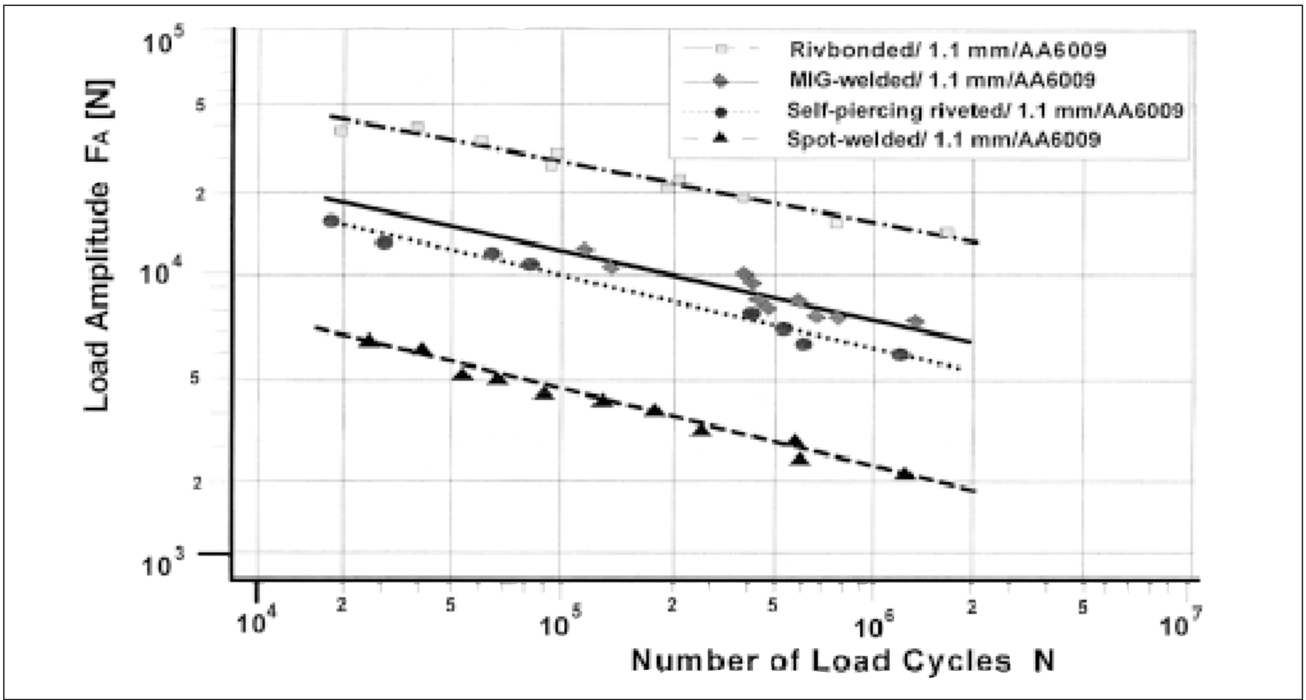


Fig. 13. Fatigue behaviour of H-shear specimens made using different joining technologies.

requires a balanced consideration of the three main interdependent factors: materials, design and last but not least, joining technology. Of special importance, in this respect, are the mechanical properties of the joints under the relevant types of loads. With the aid of examples, it was illustrated how the optimisation of the joining technology and design, the intelligent use of materials, in conjunction with a suitable joining technology, and the application of hybrid technologies can contribute significantly towards improving the properties of a structure and thus achieve weight savings.

In conclusion, the design and manufacture of lightweight structures requires that the following factors be taken into consideration:

– The forces and climatic conditions the structure is subjected to under service conditions;
– The behaviour of the joints under various relevant types of mechanical loading and environmental conditions;
– The selection and use of suitable materials;
– The selection and optimisation of the joining technology;
– The role and interdependency of joining technology, materials and design.

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