Characterisation and Simulation of Structural Adhesives

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Summary:

The analysis of adhesive bonded joints and structures relies on accurate materials data and mathematical models. In the present study the goal was to develop a method for simulating accurately, using LS-Dyna, the behaviour of aluminium structures bonded with a single part, heat curing epoxy adhesive. This required a structure with known boundary conditions and for which the substrates deformed in a predictable manner. A suitable specimen, formed from two folded aluminium tubes bonded into a T-shape, had been developed by Ford Research Center, Aachen. The MAT 169 material card was selected as a method that showed promise for use in the simulation of bonded joints.

A test programme was developed to characterise the adhesive for use with the MAT 169 material card, using tests from the British Standards catalogue. These data were then used to analyse the T-shaped structure under quasi static loading.

The results of tests and analysis of the T-shaped structures were used to assess the accuracy of the adhesive characterisation and suitability of the MAT 169 material card. A parametric study was then carried out to determine the robustness of the solutions. Once it had been established that a robust solution had been reached the results from the parametric study were used to develop an optimised set of input data for the adhesive.

Keywords:

epoxy adhesive, aluminium, finite element stress analysis, mechanical properties of bonded structures

1 Introduction

Automobile manufacturers are increasingly using structural adhesives in Body-in-White structures as a means to reduce vehicle mass. Adhesive bonding has the advantages of reducing stress concentration in joints and allowing the joining of a wide variety of materials. This increases the opportunities for introducing low density materials into vehicle structures. However, difficulties exist in the prediction of the behaviour of adhesive bonded joints using analytical methods. This limits the confidence of designers in increasing the role of structural adhesive bonding further in new vehicle designs. In the present study a typical structural adhesive was characterised and then the performance assessed in a representative bonded structure. The adhesive model used for the analysis was then studied and an optimised set of input data for the adhesive were produced based on the knowledge gained. Figure 1.1 shows how the work was carried out.

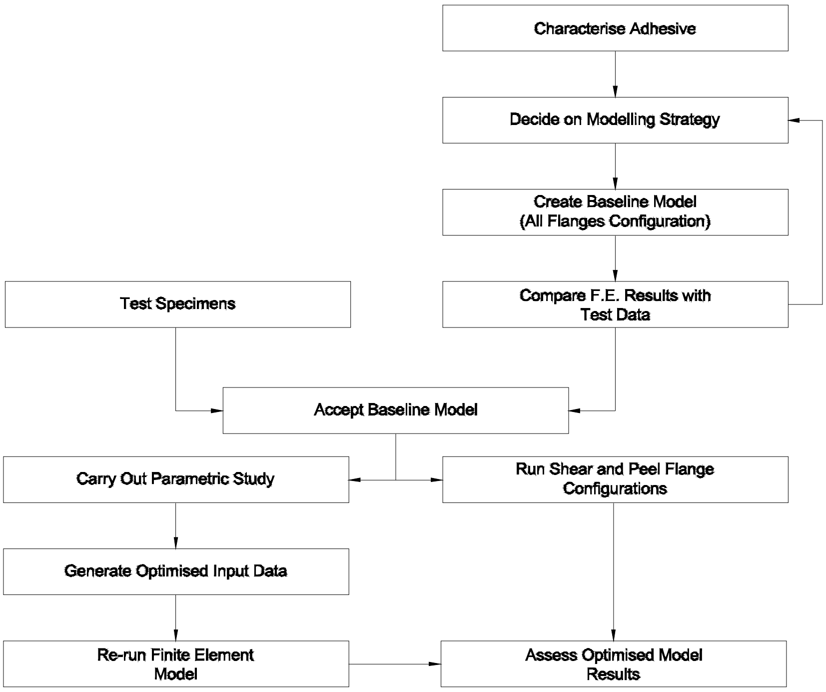

Figure 1.1 Work Flow Diagram

2 Background

The majority of the literature on adhesive bonded joints has been concerned with the testing and analysis of idealised test coupons, such as the single lap joint. Whilst such work provides great insight into the performance of bonded joints it is ultimately desirable to understand and predict the performance of more complex bonded structures.

In the automotive industry investigation of tubular structures tested dynamically in an axial crushing mode has been used extensively for the study of adhesives. Harris and Adams tested circular section crush tubes to demonstrate that adhesive bonded structures are capable of absorbing significant amounts of energy. Belingardi et al. [1] and Fay and Suthurst [2] describe similar tests on tubular components of varying cross section to develop an optimised design for adhesive bonding. A difficulty with the use of crush tubes is that the results are sensitive to the complex buckling behaviour of the metallic substrates. Furthermore, due to the dynamic nature of crush tube tests, the results are affected by superimposed oscillations and the measured response may also be a function of the loading apparatus. These issues can make subsequent analysis difficult. Some of the issues regarding analysis of crush tube tests are discussed by McGregor et al. [3].

With the foregoing in mind it can be seen that an adhesive bonded test specimen that does not experience complex deformation of the adherends during testing is desirable, since the adhesive behaviour is then a more significant factor affecting performance. A suitable configuration for this is the T-joint formed from two bonded box sections, as described by Lee et al. [4]. This design of specimen has the further advantage that the boundary conditions are relatively simple to replicate in a subsequent analysis. An additional advantage of the T-shaped joint is that the specimens are relatively inexpensive to fabricate, which allows multiple tests of the same joint configuration to be carried out.

3 Adhesive Characterisation Programme

This study was conducted using LS-Dyna version 970 Revision 5434. The input parameters for the MAT 169 materials card are shown in Table 3.1. In subsequent versions additional parameters have been introduced into the material card to allow modelling of effects such as strain rate sensitivity and adhesive (as opposed to cohesive) failure. Since these parameters were not in version 970 the parameters to be characterised were limited to those shown in Table 3.2. The rationale for selecting the material characterisation tests is discussed below.

MID	RO	E	PR	TENMAX	GCTEN	SHRMAX	GCSHR
Material ID	Density	Young's Modulus	Poisson's Ratio	Maximum Tensile Stress	Tensile Failure Energy	Maximum Shear Stress	Shear Failure Energy
PWRT	PWRS	SHRP					
Power Law Term (Tension)	Power Law Term (Shear)	Shear Plateau					

Table 3.1 Input parameters for MAT 169 material card [5]

The selection of test methods to establish adhesive properties requires a test configuration that behaves independently of factors other than the properties of the adhesive. In such tests the joint design may be unlike any practical joint used in product design. This is because the use of joint samples to establish properties is reliant upon creating a known state of stress in the adhesive layer. Only a limited number of joint designs meet this criterion. For example, the tensile butt joint (Figure 3.1) appears to generate a pure tensile load in the adhesive layer. However, this is not the case. The constraint from the adherends leads to the development of significant lateral stresses in the adhesive due to the Poisson effect. As a result, caution is required in the interpretation of the results of such tests.

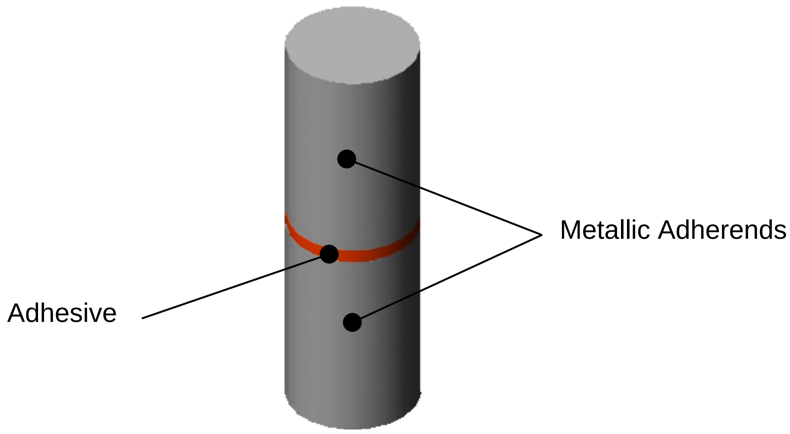

Figure 3.1Tensile Butt Joint Specimen

An example of a joint design that can be used for measuring adhesive properties is the Thick Adherend Shear Test [6]. By using very stiff adherends and a short overlap a stress in the adhesive layer that can be considered uniform shear is generated. Even in the case of the Thick Adherend Shear Test, however, the details of the specimen design, test procedure and interpretation of results all require care to generate accurate results.

A convenient alternative approach to achieving a uniform state of stress in adhesive test specimens is to manufacture bulk samples. Typically, adhesive is cast into test specimens using moulds. This approach is frequently used to measure the tensile properties of an adhesive. For example, Fitton [7] was able to generate complete tensile stress versus strain curves using bulk adhesive specimens tested in tension.

With the forgoing in mind the tests selected for adhesive characterisation are shown in Table 3.2.

Property (Symbol)	Test	Standard
Tensile Modulus (E)	Bulk Tensile Specimen	BS EN ISO 527-2:1996
Tensile Strength (TENMAX)	Bulk Tensile Specimen	BS EN ISO 527-2:1996
Tensile Failure Energy (GCTEN)	Tapered Double Cantilever Beam (TDCB)	BS 7991:2001
Shear Strength (SHRMAX)	Thick Adherend Shear Test	BS ISO 11003-2:2001
Shear Failure Energy (GCSHR)	End Notch Flexure Test	No Standard
Power Law Terms (PWRT, PWRS)	Mixed Mode Test	No Standard

Table 3.2 Material tests for MAT 169 material card

4 Specimen Manufacture and Test

It was discussed in Section 2 that T-shaped specimens offer some advantages for testing adhesives in a realistic assembly. In the present study a T-shaped joint configuration that had been developed by Ford Research Center, Aachen was used. The specimen consists of two tubular components, joined at right angles, with three adhesive bonded flanges. Two of the three flanges are loaded predominantly in peel, while the third is loaded mainly in shear. The specimens can, therefore, be assembled in three different configurations by applying adhesive to either the peel or shear flanges only, or by bonding all three flanges. The different bonding configurations are indicated in Figure 4.1.

The physical test specimens were manufactured by Jaguar Land Rover. The parts were cut from aluminium alloy that had been pre-treated using a proprietary conversion coating process. The U-shaped parts were then folded to shape from the sheet parts. Assembly of the specimens was carried out in two stages. Firstly, the flat back plate was bonded to the upper U-section. In this fabrication adhesive was applied to both flanges. The flat back plate was then added and held in place with Henrob self-piercing rivets. These were used to ensure that failure would only occur in the peel and shear flanges. Adhesive was then applied to the remaining flanges and the lower U-section placed in position to form the T-shape. Special clamps were then used to hold the parts in alignment and apply pressure to the bonded flanges during curing. The specimens were then cured using a standard cure regime based on a paint bake cycle.

Testing of the T-shaped specimens was carried out by Imperia GmbH using test equipment at Aachen University. The specimens were fitted to a special fixture installed in a universal test machine. Rigid clamp plates, retained by cap screws, were used to hold the specimen in place during testing. The specimens were then loaded at a constant rate of displacement of 1 mm•s^{-1} in the direction indicated in Figure 4.1. Data for force, deflection and time were output to a PC. These were saved on completion of each test to allow for further analysis.

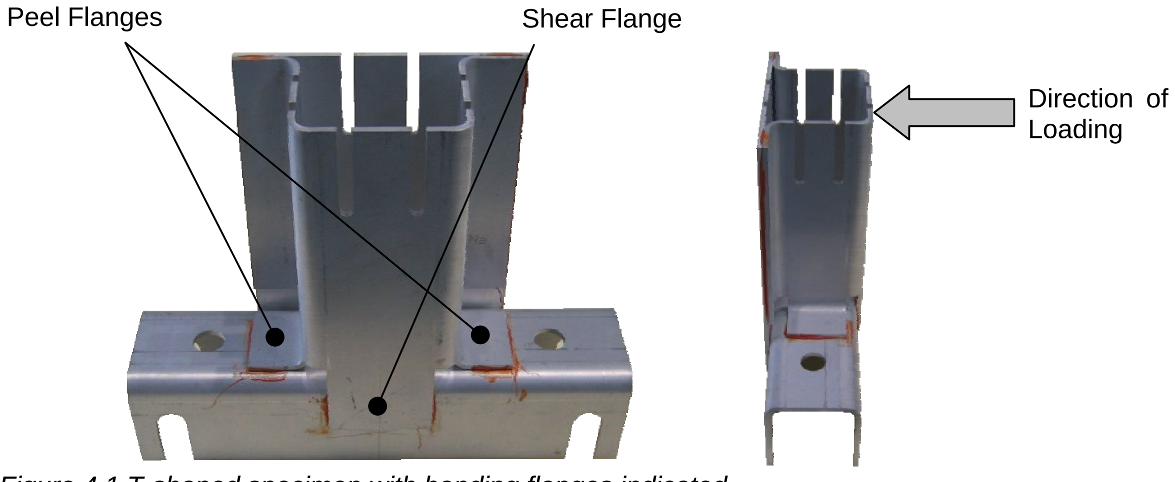

Figure 4.1 T-shaped specimen with bonding flanges indicated

5 Finite Element Analysis

A Finite Element model, suitable for use with the LS-Dyna code, was supplied by Jaguar Land Rover. The model was of the "shell-solid" type, with LS-Dyna type 16 shell elements used for the aluminium parts and type 1 solid elements used for the adhesive. The self piercing rivets were modelled using beam elements. No failure criterion was applied to the beam elements since failure was not expected to occur in the rivetted joints. The test fixture was significantly stiffer than the test specimen and was therefore modelled using rigid elements. A summary of the finite element model parameters is shown in Table 5.1.

Number of Nodes	11863
Number of Shell Elements	9965
Number of Solid Elements	416
Number of Beam Elements	13
Number of Mass Elements	2
Typical In-Plane Element Size	5 mm
Initial Timestep	6.30×10^{-7} s
Added Artificial Mass	3.11×10^{-6} kg
Ratio Added/Physical Mass	2.09×10^{-4}

Table 5.1 Summary of T-Shaped Specimen Finite Element Model Data

6 Results

Results from the baseline Finite Element analysis are shown in Figure 6.1, with the test data shown for comparison. The agreement between the analysis and test data was considered to be adequate and no refinements to the modelling method were considered necessary. The analysis was therefore run for the shear flange bonded and peel flanges bonded configurations. The results from these analyses are shown in Figure 6.2 and Figure 6.3. For the shear flange bonded configuration the results were, again, considered adequate but results for the peel configuration were less satisfactory due to superimposed oscillations on the force data. Despite this it was decided to proceed with the statistical analysis of the results and optimisation of the input data.

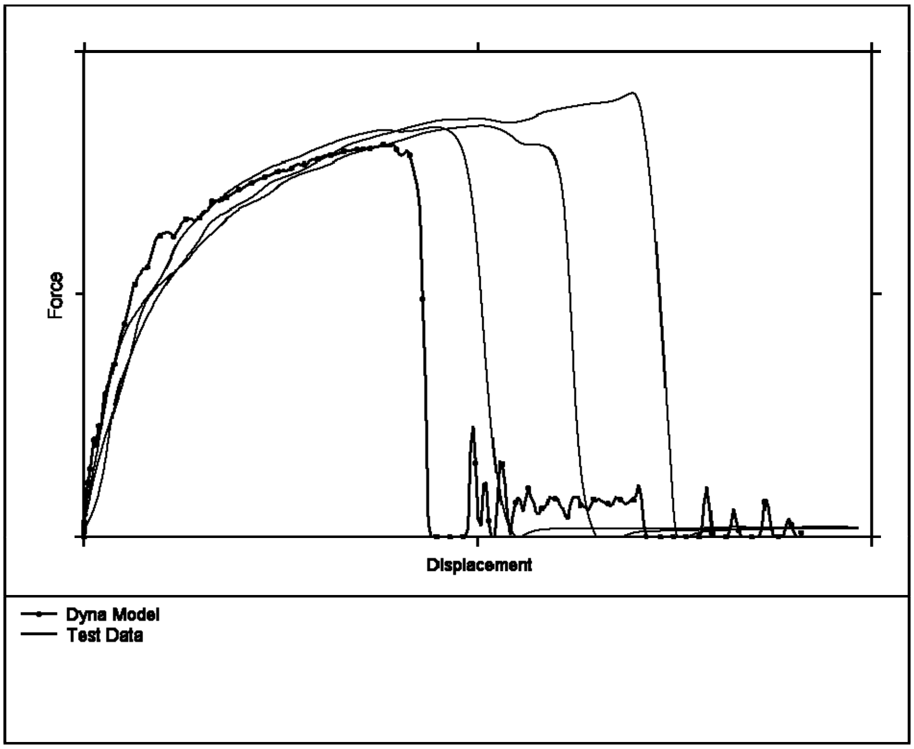

Figure 6.1 Baseline Model, All Flanges Bonded

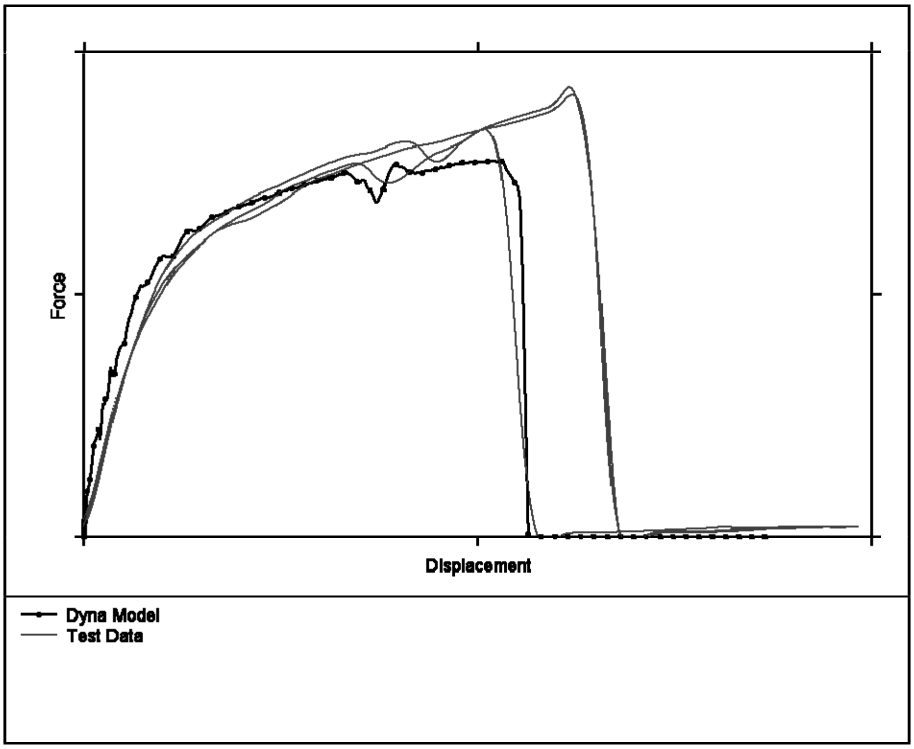

Figure 6.2 Baseline Model, Shear Flange Bonded

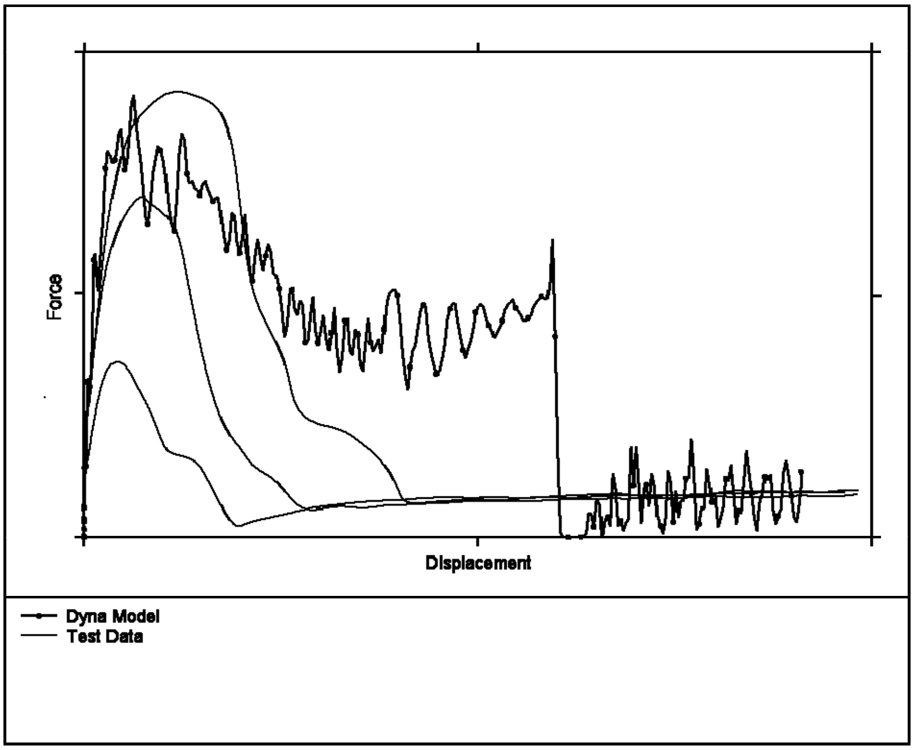

Figure 6.3 Baseline Model, Peel Flanges Bonded

7 Analysis

Having established a baseline model that exhibited adequate accuracy it was decided to investigate the effect of varying parameters relating to the adhesive behaviour in the Finite Element analysis. The parameters investigated were the shear and tensile strengths and the Mode I and Mode II fracture energies. The shear plateau parameter, that relates to the Mode II fracture behaviour of the adhesive, was also investigated due to difficulties in measuring this parameter experimentally. Each parameter was varied by ±20%, generating a test matrix of five parameters at three levels. The entire test matrix was run using multiple processors running in parallel.

Results for the displacement at failure and energy to failure were extracted from the Finite Element results. These were then investigated using the Minitab [8] statistical analysis program. The Minitab program was first used to investigate the sensitivity of the results to the inputs varied in the parametric study. Section 8 contains a discussion of the results of the parametric study. The Minitab program also contains a tool that allows the user to specify a target output for a system based on the results from a parametric study. The software then generates a set of input data to match the target output. This feature was used to match the displacement at failure for the T-shaped specimen in the shear flanges bonded configuration. The generation of the revised data is discussed further in Section 8.
The results produced from the modified input parameters are shown in Figures 6.1 to 6.3. As was expected, the results for the all flanges and shear configurations are closer to the test data. Results for the peel configuration were less satisfactory due to noise affecting the force data and because the shape of the response curve was not as accurate as for the other two loading cases.

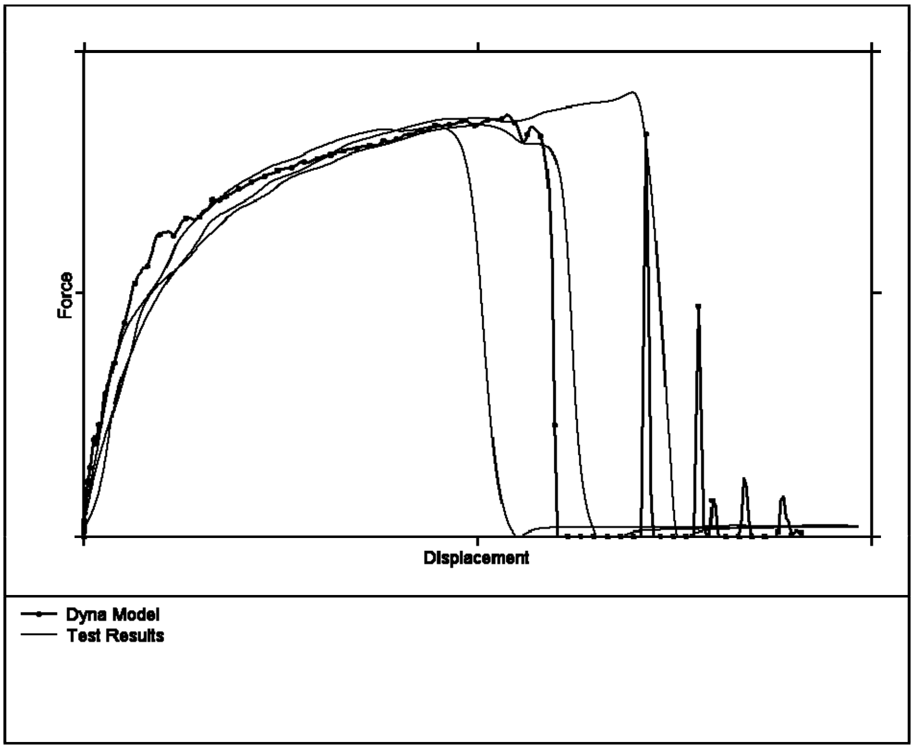

Figure 7.1 Optimised Model, All Flanges Bonded

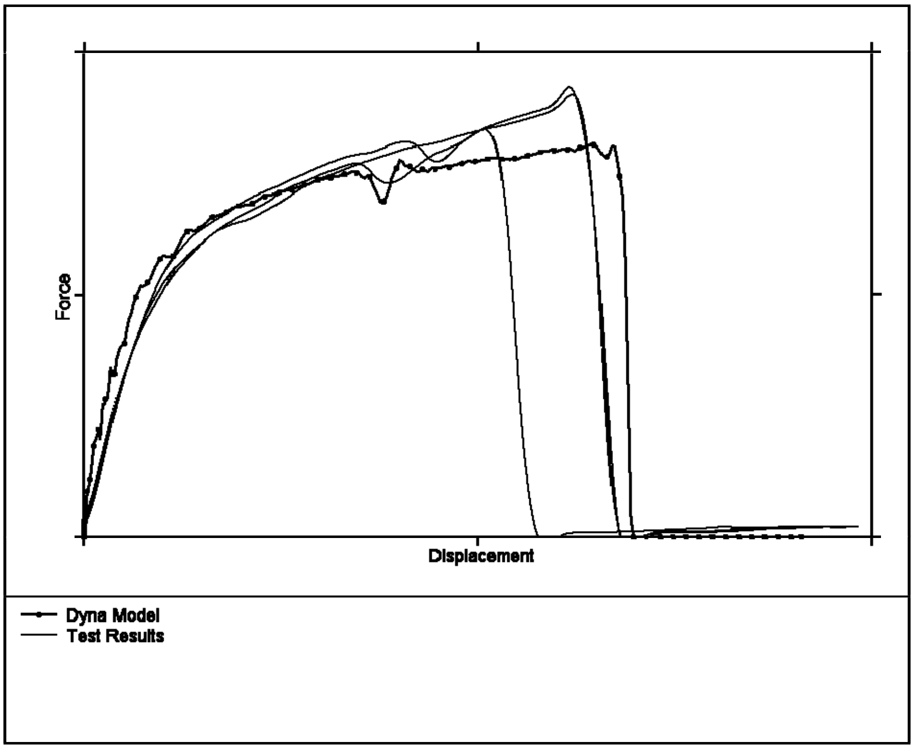

Figure 7.2 Optimised Model, Shear Flange Bonded

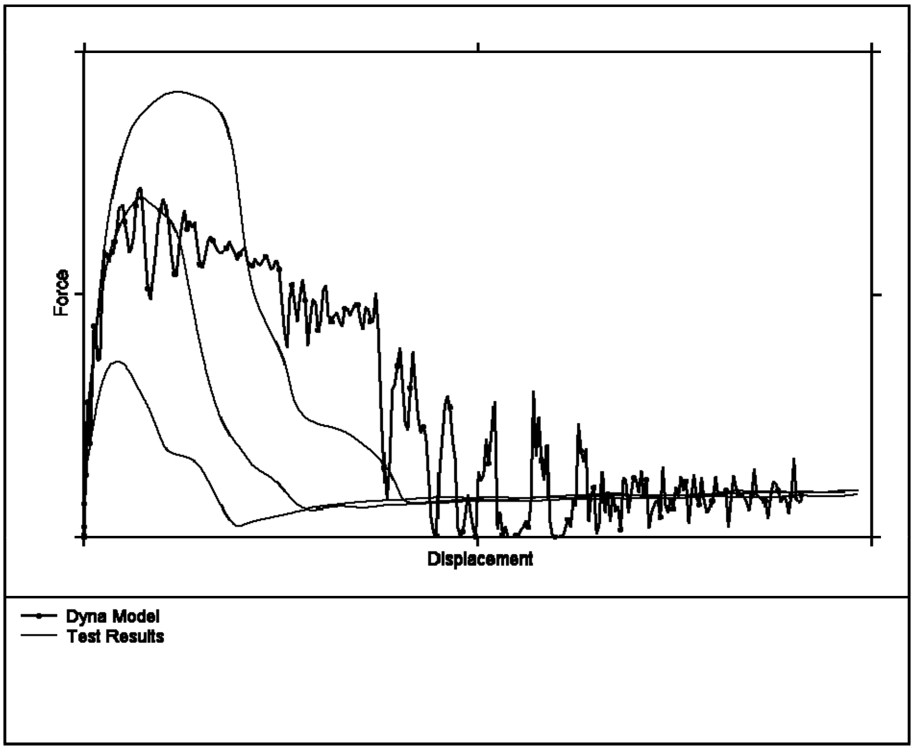

Figure 7.3 Optimised Model, Peel Flanges Bonded

8 Discussion

A baseline model was developed that showed satisfactory agreement with the test results for the all flanges and shear flange configurations. The results for the peel configuration were less satisfactory. However, it was found that changes to the adhesive materials data had little effect on the accuracy of the results. This suggests that there was a more fundamental issue with the way in which the peel flanges were modelled and that further understanding is required before the behaviour of the T-shaped specimens can be simulated accurately in all three configurations.

Although this study was focussed primarily on modelling adhesive behaviour it was found that the adhesive properties had only a limited effect on the overall accuracy of the simulation results. It was observed that the general shape of the force against displacement response was relatively insensitive to the adhesive properties entered into the Finite Element material model. This was confirmed by investigating the results of the parametric study, which showed clearly that the adhesive parameters had no effect on the shape of the force against displacement response predicted by the finite element analysis. The curves of force against displacement were the same shape with only the point of adhesive failure varying from one run to another. In the configurations with all flanges bonded and the shear flange bonded this was acceptable since the response predicted was satisfactory. For the configuration with the peel flange bonded this was not as satisfactory due to superimposed oscillations on the force data.
The parametric study suggested that the results from the Finite Element Analysis results were relatively robust with regard to the adhesive properties. Only the adhesive shear strength (SHRMAX) parameter affected the results significantly. By using the optimisation tool in Minitab it was found that the degree of correlation between the simulation and test results could be increased by increasing the value of shear strength and maintaining all other parameters as measured. This involved increasing the value from the mean average of the test values to a value at the high end of the distribution of results.
The T-shaped specimen design proved to be useful in assessing the capability to model adhesive behaviour. The ability to assemble the structure in three different configurations, with different loading modes, emphasised the need for good quality modelling techniques rather than modifying input data until a specific test result is met. This was highlighted by the fact that, as already noted, changes to the material data made no improvement to the results for the peel configuration, suggesting that there was a more fundamental issue with the way in which the peel flanges were modelled.

9 Conclusions

The results of this study showed that loading of a bonded structure could be simulated accurately using the MAT 169 material card in LS-Dyna and adhesive materials data measured using test methods described in the literature. The baseline model showed adequate agreement with the test results. In addition, the response to the optimisation process was satisfactory and led to satisfactory models for the all flanges bonded and shear flange bonded configurations. The results for the peel configuration were less satisfactory. The optimisation process demonstrated that changes to the adhesive materials data had a limited effect on the accuracy of the results, which suggests that there was a more fundamental issue with the way in which the peel flanges were modelled. It is therefore considered that further understanding is required before the behaviour of the T-shaped specimens can be simulated accurately in all three configurations.

10 Acknowledgements

The authors would like to thank Jaguar Land Rover Research and the Engineering and Physical Sciences Research Council (EPSRC), for financial support; and Ford Research Aachen for allowing the use of the T-shaped specimen design.

11 Literature

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