Assessment of Car Compatibility Performance and the Development of Improved Compatibility

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ABSTRACT

Compatibility is now recognised as the next major step forward in the improvement of car occupant secondary safety. Research is being undertaken as part of a Transport Research Foundation (TRF) funded programme to investigate modifications to an existing car design to experimentally improve its compatibility without unduly compromising its existing functionality. This paper describes the approach used to assess car compatibility based upon offset and full width deformable barrier impact test procedures, and the development of a concept modelling technique to help assess and define structural modifications for improved compatibility performance.

1 INTRODUCTION

In the UK, over half of the deaths and serious injuries to car occupants in road accidents occur when the car collides with another car (1). Research into compatibility aims to minimise overall injury severity in car-to-car impacts by encouraging car structures to work together better in a collision. It is now widely believed that improving compatibility represents the next major potential step in the improvement of car occupant secondary safety. To date, compatibility research has focused on frontal impact collisions, as this is where the greatest potential benefits can be achieved (2). This work has lead to an understanding of current compatibility problems and proposals for test procedures to assess and control compatibility (3,4,5). However, to date little work has been published on more compatible car designs, apart from a few exceptions such as Honda's ACE^{TM} concept design[1].

As part of ongoing Department for Transport (DfT) sponsored research into compatibility, performed by TRL, a current European mid-sized car was modified to improve its compatibility (5). However, these modifications were undertaken only with the aim of

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[1] ACE^{TM} – Advanced Compatibility Engineering

demonstrating the principles behind improved crash compatibility and severely compromised the existing functionality of the car. Further to this research, a separate programme funded by the Transport Research Foundation (TRF) has been initiated. The research aims to devise innovative principles to allow improvements to be made to the structural integration of current generation cars without placing any unreasonable limitations on existing functionality.

The first phase of this work is reported here. It describes an approach used to investigate car compatibility performance, the experimental application to the chosen test car and the recommendations for structural modifications to improve its compatibility. Also described is the development of a tool to calculate a section's beam element properties for input into concept type FE models. Such models are ideally suited to concept development studies, as they can be changed quickly and easily and require little computer CPU time, so that many simulations can be performed.

2 COMPATIBILITY PERFORMANCE ASSESSMENT

Research studies for frontal impact have shown that for compatibility, cars need to interact in a predictable manner to absorb the impact energy with minimal occupant compartment intrusion over a broad range of collision types. In order to achieve this, an essential prerequisite is good structural interaction. Following this some form of frontal force matching will be necessary to ensure that the impact energy is absorbed without exceeding the strength of the occupant compartment. For good structural interaction, the requirement is for multiple load paths with strong lateral and vertical shear connections, in particular at the front of the car, to ensure engagement of the opposing car structures and that the impact loads are directed into the principal energy absorbing components. For frontal force matching, the requirement is for the car frontal structure to be capable of absorbing its own impact energy without exceeding a certain force level, which has still to be determined. The compartment strength would then have to be strong enough to withstand this maximum frontal force level.

To assess and control crash compatibility a suite of three test procedures has been proposed (5). These are:

- Full width deformable barrier (FWDB) impact at 56km/h for structural interaction.
- Offset deformable barrier (ODB) impact at 64km/h for frontal force matching.
- Offset deformable barrier (ODB) impact at 80km/h for compartment strength.

It should be noted that two of these tests are adaptations of current self-protection assessment tests, so only one additional test is proposed for compatibility. The FWDB and 64km/h ODB tests are modifications of the US NCAP[2] and EuroNCAP[3] frontal impact tests respectively.

2.1 Approach

An approach to assess car compatibility performance based on the three test procedures is described below. Because these test procedures have not yet been adequately validated, the approach details an additional car-to-car test that can be used to confirm the findings of the barrier tests.

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[2] US NCAP – United States New Car Assessment Programme

[3] EuroNCAP – European New Car Assessment Programme

2.1.1 Full Width Deformable Barrier (FWDB) test for structural interaction

The purpose of this test is to assess the structural interaction potential using a measurement of the frontal force distribution measured on a high resolution load cell wall (LCW) behind the deformable face. The premise is that cars with a more homogeneous frontal resistance should offer greater potential for good structural interaction with other cars. The purpose of the deformable barrier and the development of a metric for the assessment of the homogeneity of the force distribution have been described previously (5). Further details of the test setup and the ‘homogeneity criterion’ metric are available in a test protocol (6). Since the issue of that document a revised homogeneity metric, referred to as the ‘relative homogeneity criterion’, has been developed to overcome a mass dependency problem. The relative homogeneity criterion divides the existing homogeneity criterion by the target load level squared, the target load level having previously been defined as part of the calculation of the homogeneity criterion.

The following steps are recommended to assess a car’s structural interaction potential using the FWBD test results:

- Firstly, the Average Height of Force (AHOF) (7), relative homogeneity criterion and the LCW peak force are calculated. These measures are used to compare the performance of the car with other cars tested. The AHOF gives an indication of whether the height of the car’s main structure is in alignment with that of other cars. The vertical and horizontal components of the relative homogeneity criterion give an initial indication of the car’s susceptibility to under/override and fork effect, respectively. The LCW peak force is used to provide an indication of the frontal force levels of the car in this impact configuration.
- Following this a more detailed assessment of the LCW force distribution is made focusing on the force time history recorded by each load cell. In the vertical direction an assessment of the number of load path levels, their relative distribution and strength is made. In the horizontal direction the effectiveness of lateral connections, such as the bumper beam, are determined. Structures that impact more than one load cell require that the force time histories from the impacted cells are grouped in order to determine the peak load. The barrier deformation is also examined to better understand how the car structure loads the wall. This understanding is required to determine, for example, if a car’s lower rails and bumper beam loaded one or two rows of load cells as this can potentially alter the relative homogeneity measure significantly. To further understand issues such as the contribution of power train deceleration loads to the LCW force and distribution the deceleration of the car’s constituent components is examined.
- Finally, the car deformation is examined to assess how the structure performed. From this it is assessed how the activated load paths functioned, if any components failed or were close to failure and the stability of the frontal structure.
- In addition, for good compatibility a car must also have an adequate level of self-protection. To ensure that this is the case the dummy injury criteria and occupant compartment stability are assessed. This test configuration generates a high occupant compartment deceleration pulse that is especially demanding of the restraint system.

2.1.2 Offset deformable barrier (ODB) test at 64km/h for frontal force matching

The purpose of this test is to assess the car frontal force level by measuring the peak load applied to a load cell wall (LCW) behind the deformable barrier face. Limiting the frontal force level by limiting the peak load, together with a strong compartment, will allow for each vehicle to absorb its share of the impact energy within its frontal structure without significant compartment intrusion. Details and a demonstration of this approach have been reported previously (1,2). As part of the compatibility performance assessment additional instrumentation consisting of accelerometers mounted to component parts of the car and structure are used.

The following steps are recommended to assess the car's frontal force level using the 64km/h ODB test results:

- The peak load cell wall force is used as a measure of the frontal force level. As a performance requirement for the maximum acceptable force level still has to be determined, a comparison of its results with those from other vehicles tested is made to ascertain how similar it is.
- The deceleration of the constituent parts of the car are used to determine the contribution to the load cell wall force of the deceleration of the occupant compartment and the deceleration of the mainly rigid masses forward of the firewall. This can be used to check the minimum strength of the occupant compartment in this test configuration and whether the engine bottomed out on the load cell wall towards the end of the impact.
- In addition, the frontal force distribution and the deformation of the vehicle and the barrier face are analysed to give some indication of the structural interaction performance of the vehicle in this test and confirm observations from the FWDB test assessment. How the activated load paths functioned, if any components failed or were close to failure and the stability of the frontal structure is assessed. The LCW force distribution is used to detect aggressive features. The deformation of the car and barrier is used to assess the performance of frontal lateral and vertical connections. It should be noted that a high resolution LCW measurement is required for this analysis.
- Also, for good compatibility a car must also have good self-protection. This test configuration provides a severe deformation to one side of the car that can be used to assess the occupant compartment integrity and the performance of the restraint system based on legislative and EuroNCAP protocol.

2.1.3 Offset deformable barrier (ODB) test at 80km/h for compartment strength

The 64km/h offset deformable barrier test, if the occupant compartment remains stable, will only provide information about the car's ability to cope with loads up to that generated by the car itself. It is necessary to be able to show that an occupant compartment can survive the forces imposed by another car, which may generate a higher frontal force but be within any future requirements. An offset test at an increased speed of 80km/h would provide important information concerning the strength of the occupant cabin. This test is similar to that of the 64 km/h test except that the dummies are uninstrumented as there is no requirement that cars provide a survivable performance for the occupants at this impact severity. A load cell wall is used to record the compartment strength whilst accelerometers attached to the car structure provide important information concerning the collapse mechanism of the occupant compartment.

The following steps are recommended for the assessment of the test results:

- At the end of the impact the engine has bottomed out the deformable barrier face and stopped decelerating. The load cell wall force at this point consists mainly of the occupant compartment force component and represents the load imposed on the compartment and hence can be used as an indication of the minimum load that the compartment can withstand for this loading configuration.

- If the compartment becomes unstable during the impact, it is necessary to ensure that the strength measured is prior to any major intrusion occurring. Assessment of the compartment deformation is used to determine whether the compartment became unstable during the impact

2.1.4 Frontal offset car-to-car impact test for barrier test validation

The three deformable barrier tests above should be sufficient to provide an assessment of a car's compatibility potential. However, because these test procedures have not yet been adequately validated, additional car-to-car tests may be needed to confirm the findings of the barrier tests. It is recommended that these tests should be performed with a closing speed of 112 km/h and an offset of 50 percent. This is because, if only a single test can be chosen, this configuration is the most representative of the majority of severe injury accidents (8).

In general, manufacturers aim to design their cars to perform well and predictably in a 64 ODB test, so the performance of a car in this test can be used as a benchmark. A car's Energy Equivalent Speed (EES) in a car to car test, with the configuration described above, is approximately the same as in a 64 km/h ODB test. Therefore, one way to judge the compatibility performance of the cars in the car-to-car test is to compare their relative performances in this test and 64 km/h ODB tests. If they have performed in a predictable compatible manner, with each vehicle absorbing its own share of the kinetic energy, then each car's performance will be similar to its performance in the 64 km/h ODB test. In contrast, if the cars did not behave in a compatible manner, at least one car's performance will be significantly worse than in the ODB test.

What cars are chosen for this test depends on what aspect of compatibility the engineer wishes to confirm or investigate further. For example, for aspects of structural interaction, a car to car test using identical cars would normally be recommended. If over/underride was of particular concern a test series altering the ride height of the cars could be performed to investigate in further detail.

2.2 Assessing the test car's compatibility performance

The frontal structure of the test car consists of three levels of fore/aft load paths, these being in order from the ground level up the subframe rails, lower rails and upper rails (Figure 1). Connecting these load paths across the front of the car are a number of lateral and vertical shear connections. Assessment of the compatibility performance was based on FWDB and ODB impacts test results as the 80km/h ODB test was not performed due to limited funding.

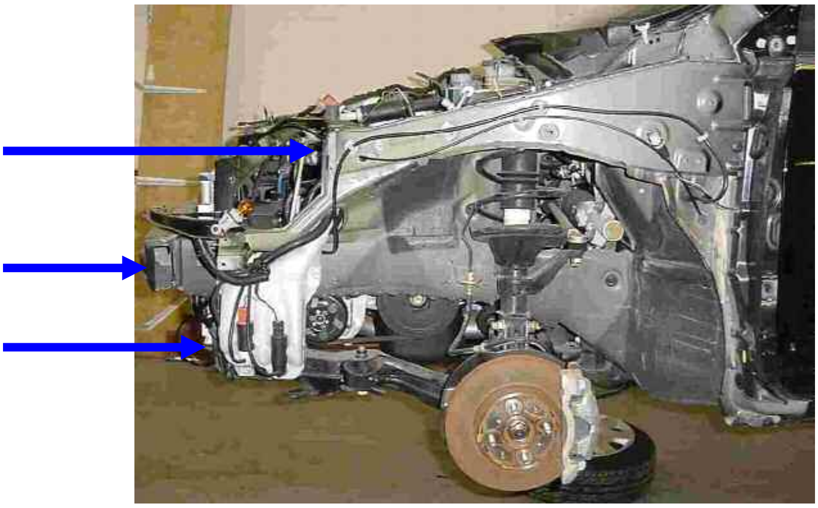

Figure 1: Side view showing the three identifiable levels of load paths, consisting of the upper rails, the lower rails and the engine subframe.

2.2.1 Full Width Deformable Barrier (FWDB) test

The resultant load cell wall force distribution for the test car is shown together with the outline of the main structural members (Figure 2). The high loads in E5:E7 and L5:L7 were generated by the impact of the lower rails, subframe rails and the vertical connections between these rails.

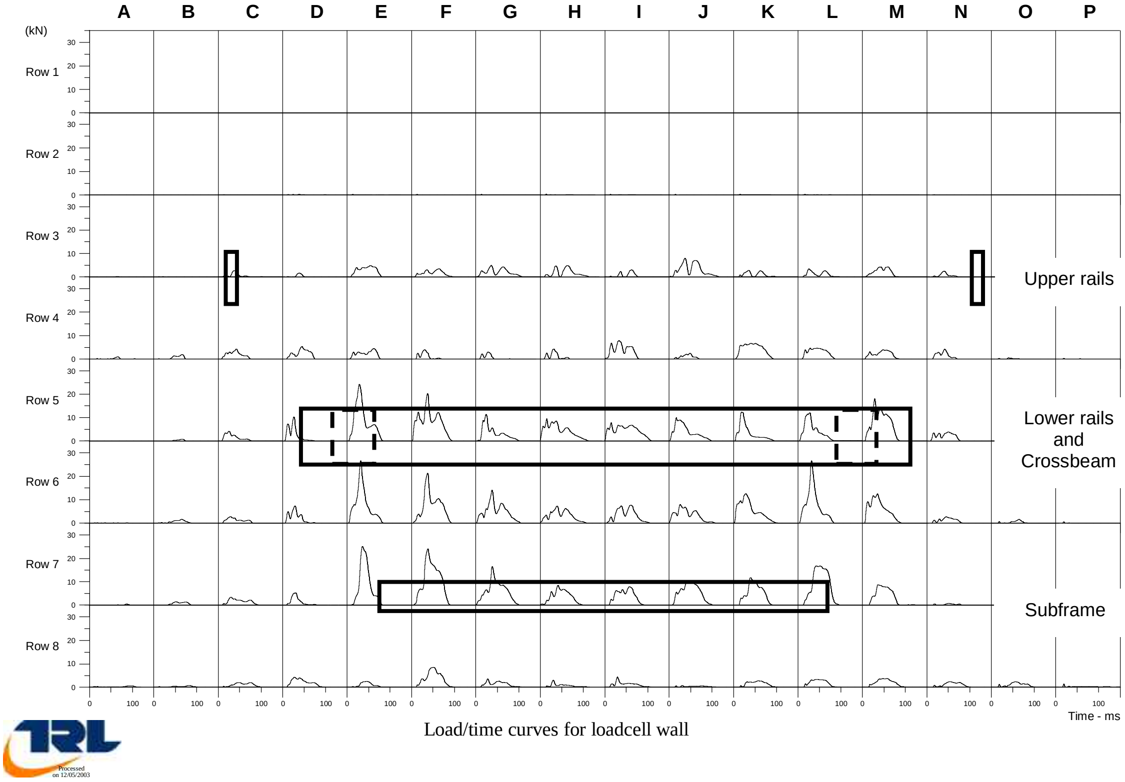

Figure 2: Force against time plot for all load cells showing the pre-impact alignment of the principle structural members.

The relative homogeneity criterion was calculated and compared with other cars that have been tested at TRL (Figure 3) (The lower the relative homogeneity criterion value the more homogeneous the frontal force distribution). It can be observed that the test car generates a less homogeneous frontal force distribution than the other cars within the same class, although it is comparable with cars those in the family class and the single small SUV. Assessment of the load cell wall force distribution showed that the high vertical homogeneity value was due to the relative difference in the load applied by the three load paths particularly the low load applied by the upper load path level, whilst the high value in the horizontal direction highlighted the low loading applied by the lateral front cross connections in comparison to that applied by the lower rail and subframe load paths. It was also noted that the alignment of the vehicle resulted in the crossbeam and lower rails bridging two rows of load cells. If this structure was to apply load to a single row of load cells then this may increase the relative homogeneity criterion.

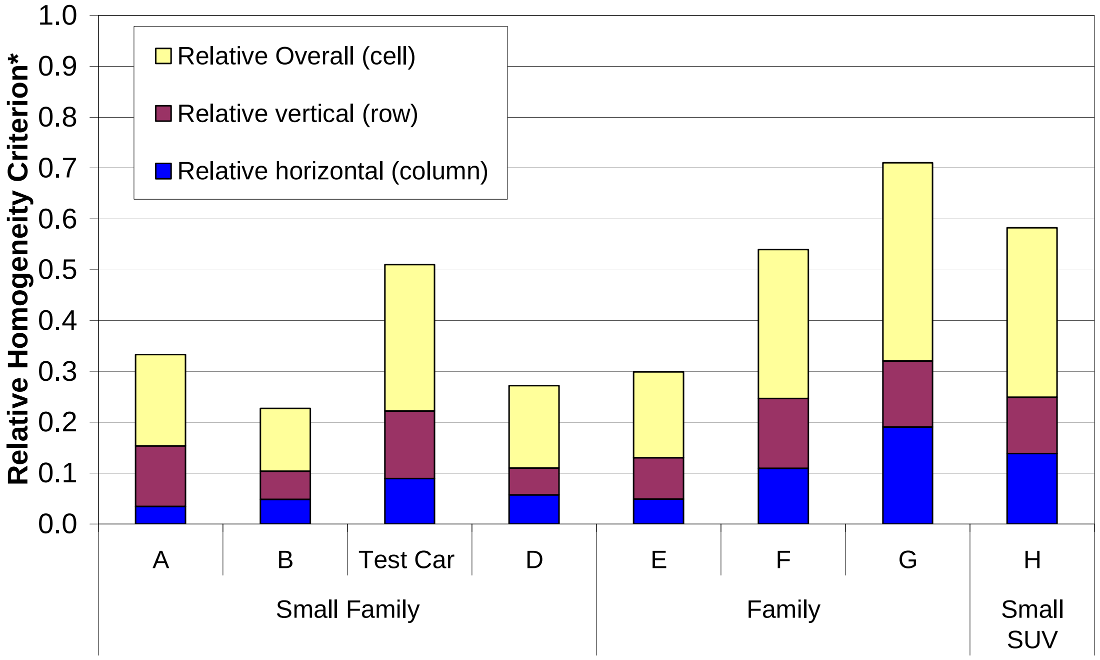

Figure 3: Comparison of test car homogeneity assessment with previously tested cars. *Note that the lower the score, the better the homogeneity assessment and that the cars are ranked in mass order.

Examination of the deformed car structure showed both lower rails and the subframe load paths failed in bending, the lower rails in the vertical axis and the subframe rails in the horizontal axis, having initially penetrated the stiffer rear layer of the deformable element. The failure of the subframe load paths and the RHS lower rail was due to narrowing of the beam cross section whilst that of the LHS lower rail was due to a discontinuity caused by the attachment of an engine mounting to the upper surface. The upper rails were determined to have been set too far back relative to the car leading edge to directly load the stiffer rear layer of the barrier face and therefore apply any significant load to the load cell wall. The RHS upper rail exhibited only minor distortion due to interaction with the softer front layer of the barrier face, whilst the LHS upper rail had failed in bending due to distortion of the shear connection with the lower rail. In terms of the lateral shear connections, both the slam panel and the bumper crossbeam were observed to have failed in bending and were displaced rearwards relative to the leading edge of the car. The slam panel failed through contact with the softer front layer of the deformable element indicating the low shear strength of this beam whilst the bumper beam failed through contact with the stiffer rear layer. The vertical shear connections between the lower rails and subframe were still connected post impact and showed no signs of failure.

In terms of the self-protection, all the dummy injury criteria were below the EEVC injury limits. However, there was a potential concern regarding the contact of the driver's chest with the steering wheel. This may require retiming of the restraint system.

2.2.2 Offset deformable barrier (ODB) test at 64km/h

In the offset test the peak load cell wall force was 410kN, the structural component was 310kN. The majority of this force was applied by the impacted side lower rail and to a lesser extent subframe load path. Although it has yet to be determined what level the maximum frontal force level should be set in order to encourage compatibility, the peak force recorded by the test car is comparable to those cars within the same class that have been tested as part of EuroNCAP (Figure 4).

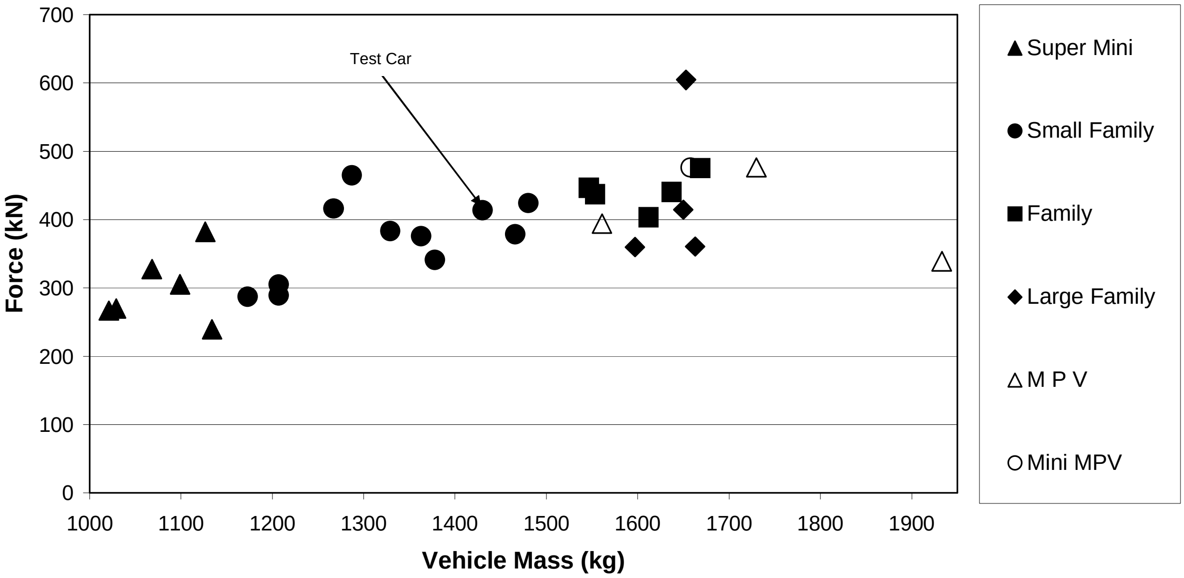

Figure 4: Comparison of the peak load cell wall force for the test car with other cars tested for EuroNCAP.

The deformation of the car front and barrier face indicated no potentially aggressive structures. The slam panel was displaced rearwards relative to the leading edge of the car structure through contact with the deformable element, the performance of the slam panel in this test configuration confirming the earlier observation from the full width test regarding the weakness of this connection in shear. In addition, it was noted that the front wheel on the impacted side had been displaced rearwards and came into contact with the sill forming an additional load path between the barrier face and the occupant compartment.

In terms of the self-protection, the compartment remained stable based on EuroNCAP protocol and the dummy injury criteria were all below the EEVC injury limit requirements.

2.3 Conclusions and recommendations

Based upon the performance of the test car in FWDB and ODB test configurations the following conclusions and recommendations can be made regarding the compatibility performance:

- The relative homogeneity criterion was higher than for other cars within the same class although there was a good balance between the loads applied by the lower rail and subframe load paths. Improvement of homogeneity in the vertical direction would require that the load applied by the upper load path level is increased by increasing the crush strength and bringing structure further forwards towards the leading edge of the car. This would help reduce the potential for the car to be overridden in an impact with a car that has a higher frontal structure. In the horizontal direction, the requirement would be to increase the shear strength of the bumper crossbeam and slam panel to prevent lateral fork effect in collision with other cars. In addition, increasing the frontal area of the subframe crossbeam would create a larger pushing surface which would benefit in engaging other car structures and provide a more homogeneous frontal force distribution on the load cell wall, although the effects of additional structure forwards of the front axle on ride and handling must also be considered.
- There was good stability of the structure in the vertical direction, the lower rails failing in bending about the vertical axis minimising movement of the structure in the vertical direction during the impact.
- The frontal force level of the test car in the offset test was 410kN, although no maximum acceptable force level has yet been specified for this test, this performance was comparable to other cars tested at TRL indicating that any structural modifications should aim to limit the overall increase in the frontal force level in this test configuration. The occupant compartment remained stable and the minimum compartment strength in this loading configuration was determined as 310kN.
- The lower vertical shear connection was effective in deforming the offset impact barrier. However, the upper vertical shear connection was a single panel and was not able to interact effectively with the barrier face. The frontal area of the upper shear connection would ideally need to be increased to promote interaction with the lateral crossbeams of another car that may lie between the height of the lower and upper rails of the test car.
- The test car met self-protection requirements concerning dummy injury criteria in both the full width and offset impact test configuration based on EEVC injury limits and the compartment remained stable based on EuroNCAP protocol. However, there was a possible concern regarding the contact of the driver’s chest with the steering wheel in the full width impact test. This may require retiming of the restraint system.

Modifications of the type recommended above will be incorporated in another test car and evaluated as part of the ongoing programme of research.

3 CONCEPT MODELLING TECHNIQUE DEVELOPMENT

For concept development a model should be able to be changed quickly and easily and require little computer CPU time so that many simulations can be performed. Full scale Finite Element (FE) models are not ideally suited to this as they have large CPU requirements and alterations to the model can sometimes be time consuming. To overcome these problems smaller concept type FE models can be used, which use beam elements to represent the car’s main structural members and shell elements with a coarse mesh to represent the large panels

(Figure 5). Although this type of concept model is not as accurate as a full scale FE model, it is simple to alter and computationally inexpensive. However, to be able to use it, an efficient way to estimate the beam element properties is required.

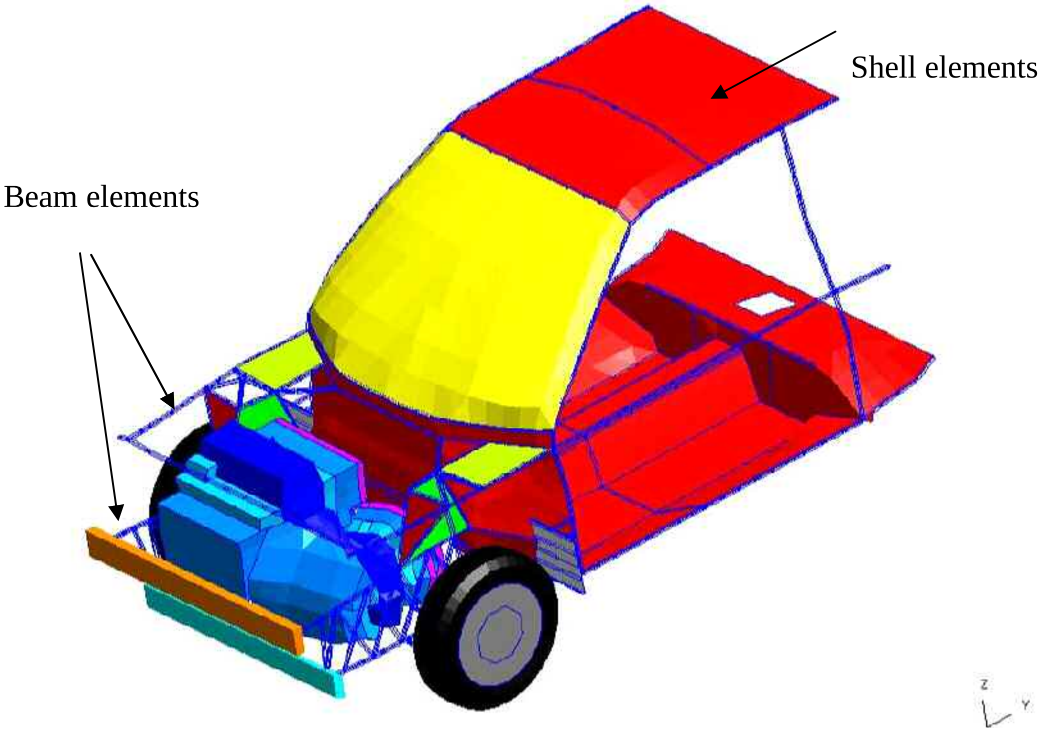

Figure 5: Concept model showing extensive use of beam elements.

The 'MAT_MODIFIED_FORCE_LIMITED' material model in the LS-DYNA[4] software represents a beam's plastic properties using a non-linear translational spring for axial crush and non-linear rotational springs for plastic bending. The reduction in a section's bending moment strength under axial loading is also represented by making the beam's plastic bending properties a function of the axial load. This technique is referred to as 'load mode coupling', and is important when modelling car structures which are subjected to high axial loads. A tool to estimate the beam element properties of a section and translate them into a format suitable for input into the 'MAT_MODIFIED_FORCE_LIMITED' material model in a LS-DYNA input deck has been developed. This tool can also be used to estimate possible section sizes for given axial crush and bending moment requirements. The development and validation of the methodology on which this tool is based is described.

3.4 Development of the Methodology

3.4.1 Axial Loading

Under axial load, a thin-walled member will fail either in axial crush or in Euler buckling. Whether it will fail in axial crush or in buckling is determined by its slenderness ratio. In axial crush the difference between the critical stress of the section and the material's yield stress will determine whether the member will crush regularly or irregularly. A regular fold is preferable as irregular folds will induce bending moments, possibly causing the whole columns to fail in bending, hence absorbing less energy. The critical stress value depends on

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[4] LS-DYNA is an explicit dynamic non-linear finite element solver.

the smallest t/b ratio of the section, where t is the thickness and b the width of the buckling (largest) plate.

When a tube is crushed axially, the force versus strain characteristic has two main features; the peak load and the mean load. The peak load value determines the force needed to trigger the collapse mechanism. Its value is determined by the stress concentration in the section's edges. The mean load determines the amount of energy the member will be able to absorb by crushing (9). For a rectangular section, the peak load is always greater than the mean load (between two and ten times). For a circular section, the peak and mean load will have very similar values.

For the current methodology, the mean load is calculated using an empirical formula. The peak load is estimated as being twice this value. This simplification is based on the assumption that automotive structures rarely behave as compact ones. Such structures have indentations, pressing defaults, holes for component fitting and are spot-welded. These defects will reduce the peak load substantially. The formula used to estimate the mean load in the current methodology was determined experimentally (10) using square steel columns. The formula gives reasonable results for the range (0.008 < t/b < 0.025) which is typical for automotive structures:

$$P = 4.25A\left(\frac{t}{b}\right)^{0.8}\sigma_{ult}$$

A: cross sectional area
t: thickness
b: width of buckling plate
σ_{ult} : ultimate stress

The maximum engineering strain value used for crush was the experimentally determined average value of 0.728 (11).

3.4.2 *Pure Bending*

Plastic bending is initiated by buckling of one of the section's panels. Depending on the difference between critical stress and yield stress, three types of failure can be obtained; elastic buckling, plastic buckling or mixed mode. Semi-empirical formulae exist for these three types (12). The idealisation process used in the current methodology calculates the critical stress and uses the following equation to estimate the initial plastic bending moment, which gives a compromise between the three possible failure types:

$$M_{P0} = C.\frac{\sigma_{cr} + \sigma_y}{2}.I_P$$

C: shape factor determined experimentally (0.93 recommended for rectangular sections)
σ_{cr}: critical stress
σ_y: yield stress
I_p: primary moment of inertia.

Another critical point regarding bending of thin-walled tubes is the jamming angle (angle for which buckling walls contact inside a plastic hinge). When the plastic hinge's angle exceeds this value, its moment may start increasing again or continue decreasing, depending on the section's shape, its orientation and the material's thickness (13,14). Practical experiments rarely reach the jamming angle. To overcome this lack of experimental data, many detailed finite element simulations were carried out for a range of sections typical of automotive structures. From these an average plastic bending characteristic was determined. The ratio between the plastic moment and the initial plastic moment was estimated for various angular values. An artificial lock up occurs at Θ=90° to maintain model stability and limit the amount of energy a hinge can absorb.

3.4.3 Load Mode Coupling

Practically, when any member is loaded axially as well as in bending, the value of the initial plastic bending moment is decreased compared to when it is not loaded axially (14). The material model used in LS-DYNA uses coupling tables to represent this effect. Detailed finite element simulations of sections loaded simultaneously axially and in bending were carried out to develop a coupling curve. Another curve was also derived using the fully plastic theory equation shown below:

$$\left(\frac{M}{M_{P0}}\right)+\left(\frac{P}{P_m}\right)^2=1$$

M: plastic bending moment
M_{P0}: initial plastic bending moment
P: Axial load
P_m: Mean crush load

Comparison of these curves shows close agreement except at high axial loads (Figure 6).

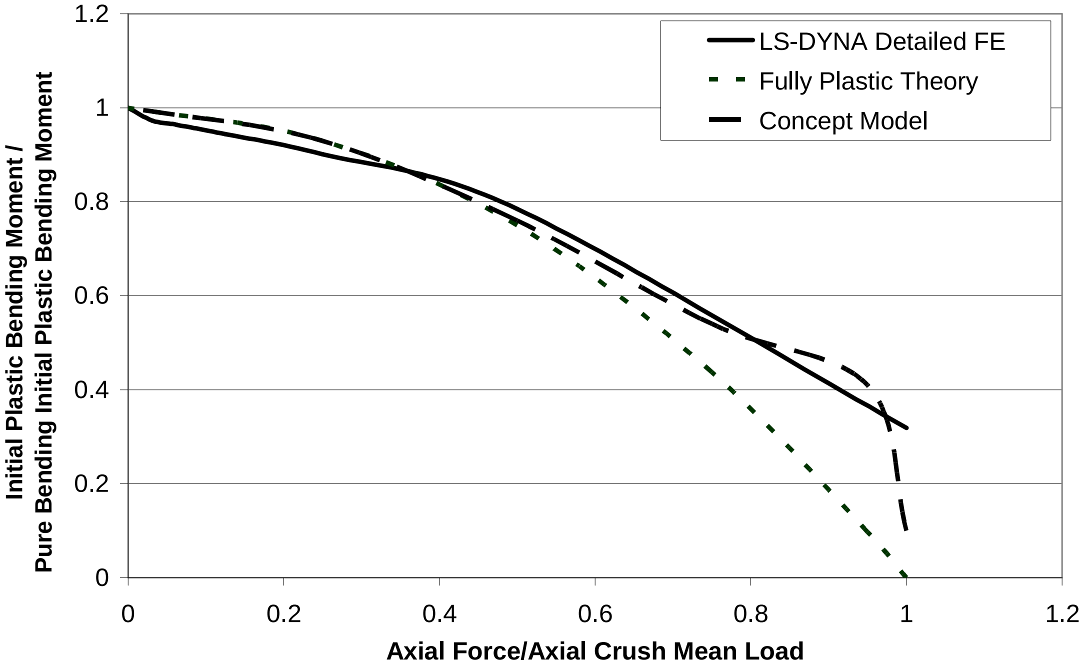

Figure 6: Comparison of coupling curve used in the concept methodology with those derived.

3.5 Validation of the Methodology

To validate the methodology experimental results were compared with predicted results. However, as not many experimental results could be found in the literature, the methodology was further validated using detailed FE simulations to generate more data for axial crush and pure bending loading conditions. All the simulations were performed at low speed (5m/s). In reality structures may deform differently when impacted at high speed as inertial effects and strain hardening can become significant.

3.5.1 Axial Crush

The prediction of the mean crush force was reasonable for rectangular sections with a t/b ratio between 0.007 and 0.02 (Figure 7). However, the prediction of the peak load was not as good. Realistically, while the peak load under quasi-static test conditions is fairly repeatable, under dynamic loading conditions the peak load of automotive sections will be extremely sensitive to parameters such as the impact speed and material defects. Therefore even detailed FE simulations would not be very reliable in estimating peak load.

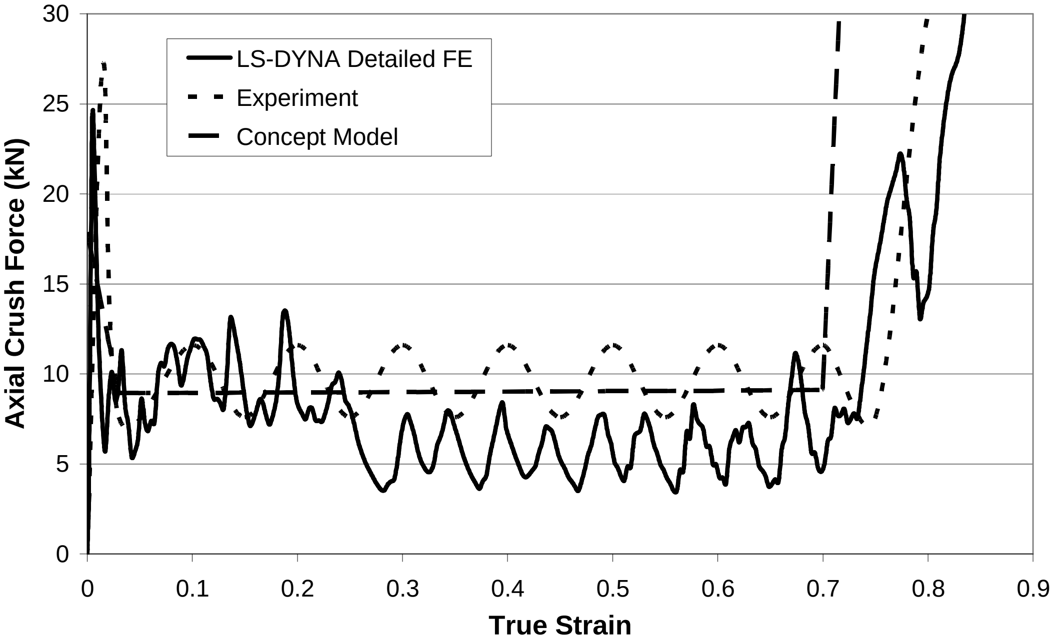

Figure 7: Load vs Strain curve for axial crush showing comparison between experiment and detailed FE and concept methodology predictions.

3.5.2 Pure Bending

The prediction of the initial plastic bending moment compared well with the experimental data and the detailed FE simulation (Figure 7). However, past the initial value, the predictions are not so good. For the case shown the bending moment is initially under estimated and later over estimated. In addition, the methodology always predicts a rise of the bending moment value past the jamming angle, which is incorrect as this is dependent on the height / width ratio of the section. However, it is even difficult to model this effect accurately using detailed FE simulation unless a very fine mesh is used. Once a reliable detailed finite element model is developed, this problem should be addressed.

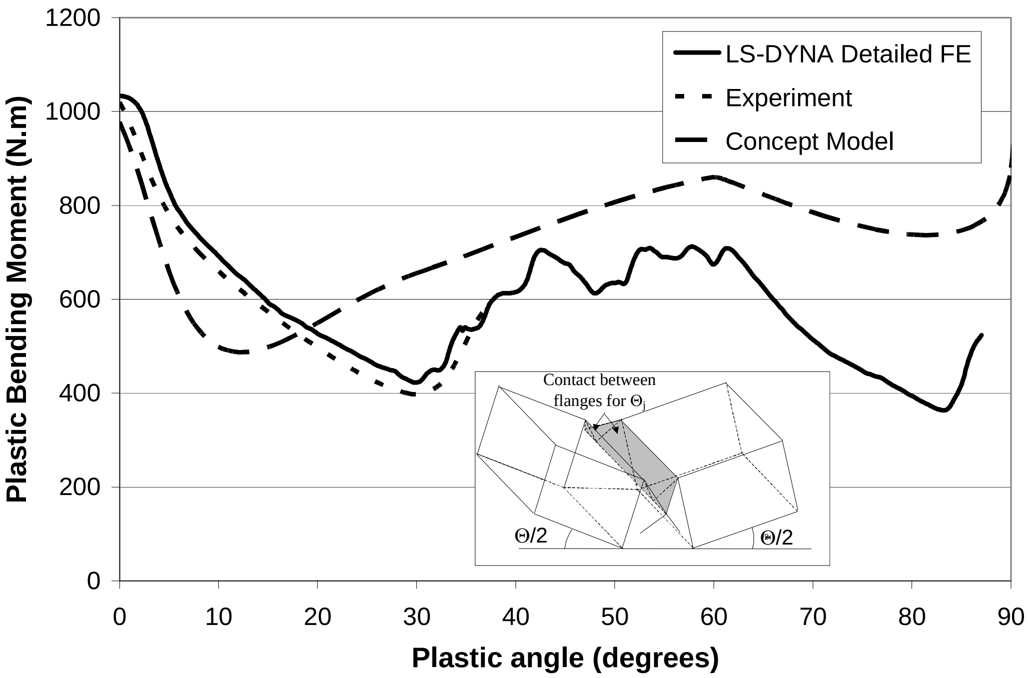

Figure 8: Plastic moment vs plastic angle curve for pure bending load showing comparison between experiment and detailed FE and concept methodology predictions.

3.6 Conclusions

For initial concept design type studies models are required that are simple to alter and computationally inexpensive. Simple FE models that use beam elements to represent a car's main structures are suitable for this type of work. A tool to estimate the beam element properties of a section and translate them into a format suitable for input into the 'MAT_MODIFIED_FORCE_LIMITED' material model in a LS-DYNA input deck has been developed. This tool can also be used to estimate possible section sizes for given axial crush and bending moment requirements. However, it should be noted that the methodology on which this tool is based has only been validated for a limited range of section sizes and shapes, i.e. simple thin walled rectangular and square sections with a t/b ratio between 0.007 and 0.02, where t is the thickness and b the width of the buckling (largest) plate.

4 ACKNOWLEDGEMENTS

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