THEORETICAL ANALYSIS OF UNPROFESSIONAL REPAIRS ON QUALITY AND SAFETY OF ROAD VEHICLES USING FINITE ELEMENT METHODS

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INTRODUCTION

Finite element modelling of a car assumes the body is composed of a certain number and variety of substructures with well-defined physical properties. When that same car is unprofessionally repaired it disturbs the original production vehicle's physical properties and as a result poor occupant protection is demonstrated by failure mechanisms of the body structure with excessive intrusions in the safety cell. To quantify the protection capability, normally two analysis fields are used in which highly nonlinear conditions are simulated under crash of assembled structures in a complete car model and crush analysis involving energy absorbing elements. The purpose of crash and crush analyses is to appreciate the performance of car structures and its components under various accident scenarios.

It is a fact that car bodies in accident situations are loaded differently and therefore crumple zones definition is required for improved occupant protection. These are the highly effective and well balanced structural energy absorbing cocoons that safeguard the survival space from the front and the rear of the vehicle. Safety is not only controlled through crumple zones [1]. To achieve the level of safety required in state-of-the-art designs, it is advisable to optimize the car body vis-à-vis load path. Production vehicles have clear defined load paths that enable them to distribute the stresses and strains evenly thereby maintain the car work in elastic range for a larger part of its life cycle. With unprofessional repairs, that balanced load path is disturbed and the risk to occupant injury under an accident condition is increased many folds.

For clear quantification of the level of safety in unprofessional repaired car body, finite element analysis is employed. The loading and computer simulation results ought to be fairly close to the experimental or real world accident data since this is a non-linear process. In this paper LS-DYNA 3D code is used [2]. It was developed based on explicit time integration, special shell elements for this specific analysis and modelling assumptions regarding the dynamic behaviour are involved. To solve the problem in virtual environment that will emulate a practical method small time steps are used.

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THEORETICAL CONSIDERATION USING ANALYTICAL METHOD

To try and understand the principal of a crushing structure subjected to impact loading it is always recommended to go back to fundamentals and build a theory from there. It is known that a vehicle during an accident process can be defined as a dynamic system vibrating. Therefore we can say the equation of the dynamical system vibrating is given as

$$\blacksquare\,\Omega\,\blacksquare\;\ddot{\delta}(t)+\blacksquare\;\psi[\dot{\delta}(t)]\;\blacksquare\;\dot{\delta}(t)+\blacksquare\;K\,[\dot{\delta}(t)]\;\blacksquare\;\delta(t)=\vec{P}(t) \qquad (1)$$

What equation (1) indicates is that damping and stiffness matrices depend on grid point displacements. In crashworthiness problem grid displacements may be in thousands and therefore accumulate a lot of time to achieve a converging solution.

This works well when assessing a problem using multi-body rather than FE method. The simple reason is that it considers more of the linear part of the load displacement characteristic and hence works well solving linear problems. To take into consideration the non-linear characteristic, a non-linear fraction based on shock absorber rate can be used by presenting all stored non-elastic energies per unit δ as the sum of linear and non-linear fractions. This is given as

$$\blacksquare\;\psi[\dot{\delta}(t)]\;\blacksquare\;\dot{\delta}(t)=\blacksquare\;\psi*\blacksquare\;\dot{\delta}(t)+\blacksquare\;\left(\frac{\varepsilon}{\delta}\right)[\dot{\delta}(t)] \qquad (2)$$

Substituting Equation (2) into (1) and considering time step integration, a final equation for the dynamic system is obtained as

$$\blacksquare\,\Omega\,\blacksquare\;\ddot{\delta}(t)+\blacksquare\;\psi*\blacksquare\;\dot{\delta}(t)+\blacksquare\;K*\blacksquare\;\delta(t)=\vec{P}(t)-\left(\frac{\varepsilon}{\delta}\right)[\dot{\delta}(t-\Delta t)] \qquad (3)$$

For first approximations, this is adequate and gives some answers needed to size the system. The drawback with this method is that it does really show the plastic regions and how those affect the overall vehicle structure performance as the car permanently deform. To do that finite element (FE) is really the best method to use in impact and crashworthiness problems.

THEORETICAL CONSIDERATION USING FINITE ELEMENT METHOD

Finite element method is now widely used in crashworthiness problems to yield accurate results. There are number of codes and LS-DYNA 3D is one of the mostly used in industry and academia. The code has been developed based on explicit time integration, special shell elements for specific analysis, and modelling assumptions regarding the results have been compared with experimental test data, and the simulations have proved to be very valuable and accurate.

The accuracy of the simulation is optimized by giving each element certain numerical attributes that affect the properties. As stated earlier when assessing the analytical method, this is acceptable because the computation time for a given space state grows with its size much faster than the amount of memory it requires. When that happens, allowable computation time becomes limited before usable memory runs out. This also happens when improving the accuracy of the solution.

To reduce the time, optimization might be required [3]. There are numerous optimisation techniques. The one that works well for large non-linear deformations is the optimization technique that improves the speed of the code while maintaining efficiency. This involves separating particles into cells according to their position. Under this method, all particles in the system whose positions are within a given cube of space are grouped into a single cell. This associates particles with those that are near them spatially. The sorting involved, takes place at the beginning of each iteration and each particle interacts only with those particles that are in its cell or adjacent cell that can only be used if cell interaction with the adjacent cells are located in a relative proximity to the centre of its cell. Since the physical relationships in the system diminish as inter-particle distance increases, this restricts the computations to those that cause the most significant changes in the simulation state [4, 5].

Vehicle Modelling

To really understand all the effects of poor repair, it is necessary to develop a sound validated finite model for parametric studies [6-9]. A Ford Fiesta CAD was obtained and meshed using principally elements with Belytshko-Tsay formulation, Figure 1.

Number of Parts	351
Number of Nodes	183609
Number of Solids	1000
Number of Beams	304
Number of Shells	176568
Number of elements	178063

Pre-Processor	LS-PREPOST and Oasys Primer
Solver	LS-DYNA 3D
Post-Processing	D3PLOT and LS-PREPOST

Figure 1: *Finite model of the Ford Fiesta*

The test protocol employed during the experiment of the VW Passat was implemented in virtual testing representing similar boundary conditions and loading rates. LS-DYNA3D solver was employed for simulation.

Figures 2 and 3 show a developed Ford Fiesta model that has been validated against EURONCAP 40% offset frontal impact into a deformable barrier and the pole test.

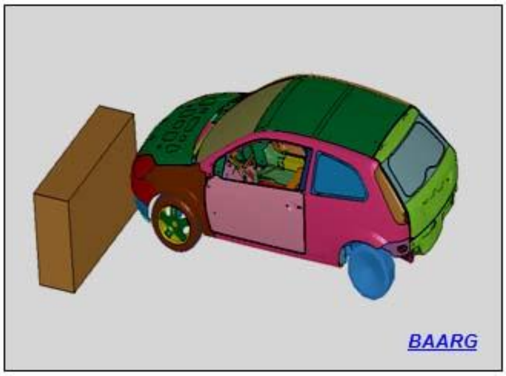


Figure 2: *Ford Fiesta developed model for against virtual testing*

Figure 3: *Ford Fiesta Model validated EURONCAP 40% offset frontal impact*

To assess the vehicle performance alone without the contribution of the deformable barrier, it was necessary to impact the Ford Fiesta into a rigid barrier at 55 kph that is equivalent to 64 kph into deformable barrier. The load time history from that simulation of the original model is given in Figure 4.

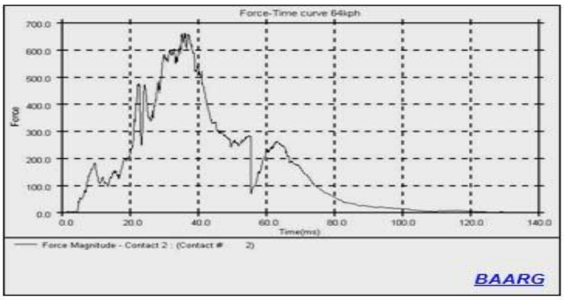


Figure 4: *The Force time characteristic showing collapse sequence of the original body-in-white*

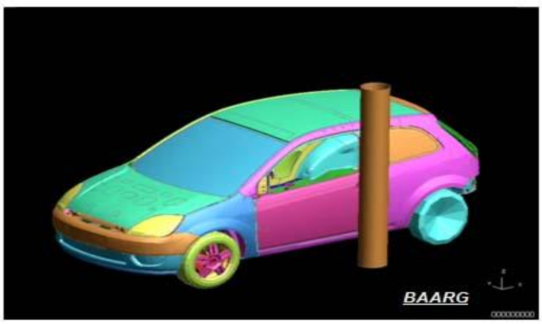


Figure 5: *The Ford Fiesta under pole impact*

Once the original model was working, it was necessary to introduce an accident into the equation. Therefore a pole test was chosen to simulate the side impact into a tree or lamp post at 18 mph (29 kph), Figure 5.

Figure 5 shows the Ford being driven into a pole as per EURONCAP test. Once the deformations from the pole tests were quantified and analysed, it was then possible to carry out repairs in the deformed side structure by virtual panel beating the structure and carrying out some welding at chosen locations.

To start the collapse behaviour study of unprofessional repairs, it was necessary to introduce some defects into the model that represent typical bad workmanship. The numerical results show some common defective elements between the experimental vehicle and the numerical Ford Fiesta as follows:

The Effects of Joining Methods

In unprofessional repairs, the method used for joining structural components after panel beating is by arc welding and sometime reverting. Few accident repairs are done by spot welding which is the method used by OEMs and its agents. In using these alternative methods, the vehicle structures' joints introduce new load path capability while at the same time either weaken the location of the joint or strengthens it beyond the original strength hence diverts the original load path. To maintain the original structural capability at the repaired joint the whole component need to be changed and spot welded in appropriate locations [10].

The weakening of the joints comes about from a number of factors:

- Welding temperature. This will influence the joint strength and if too high the material in the vicinity of the arc welding will have high thermo stresses that will soften the material and hence develop residual stresses. As a consequence this will reduce the allowable stress and failure may be premature with little performance of work. If the temperature is low, the joint might not be properly connected to its full potential and hence also premature failure may occur due to reduced allowable strength. To have a good joint, the welding regime employed by the OEMs must be followed. Unfortunately, small garages have no such capabilities and therefore will use unregulated tools to connect structural components. As a result non-uniform heating that causes non-uniform expansion and contraction develop distortions and internal stresses within the weld.

- Feed speed and weld quality. These two factors affect the joint strength in one form or another. In arc welding the feed speed is important in that the weld is calibrated to its potential strength. The higher the speed the more heat the material will release and the temperature in the working region will rise. The temperature that car body steel is heated at, the length of time it is held at that temperature and the rate that it is cooled, all have an effect on the metal's crystalline structure or commonly referred to as microstructure. The weld quality under these circumstances may develop microstructures in the weld zone that are detrimental.

In order to demonstrate the phenomenon of reduced strength in regions that have been joined after being subjected to bad repair attributed from heat or built up residual stresses, the original model in Figure 2 was weakened in three locations, namely the upper A-pillar, Roof rail B-pillar joint and the sill as shown in Figure 6.

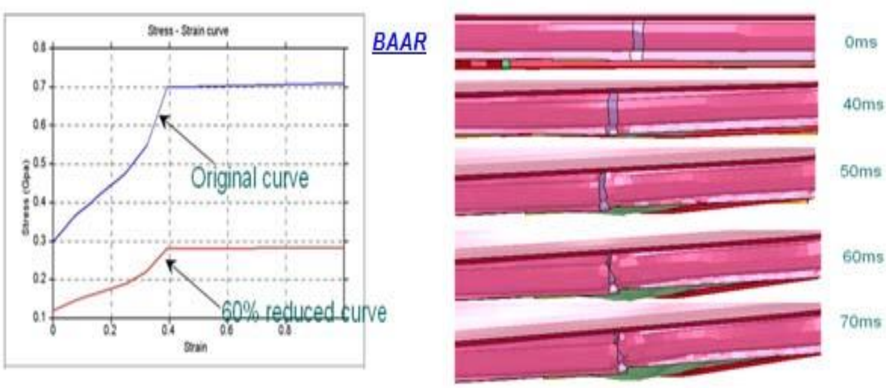
a) b) c)

Figure 6: *Stressed locations that show all round the periphery defect in the joint*

After the defects were built in the model by reducing the strength at those locations by up to 60% (MODE I) as given in Figure 7a, typical results thereof are shown the figure 7b.

The Effects of Panel Beating Quality

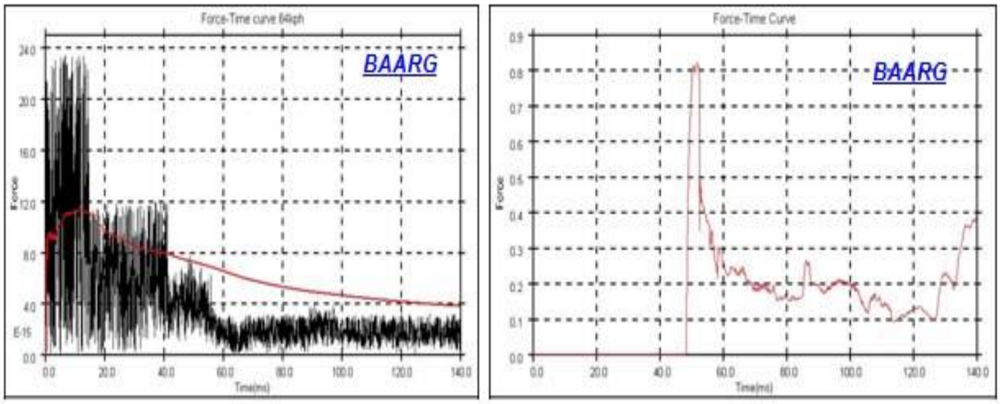
In OEMs' appointed workshops repairs are all done under the control of the panel beating regime. In unprofessional repairs, the panel beating is normally done by pull, temperature rise through the introduction of heat and hammer to flatten the surfaces. This reduces thickness in some locations around the periphery resulting to a greater extent in uneven stretching in the cross section of the repaired components. The other outcome from such a repair is the introduction of geometrical tolerance variations such as the changed I-value of the cross section, change in torsional constants and general cross section properties. In some of these cases prompting warping effects.



a) b)

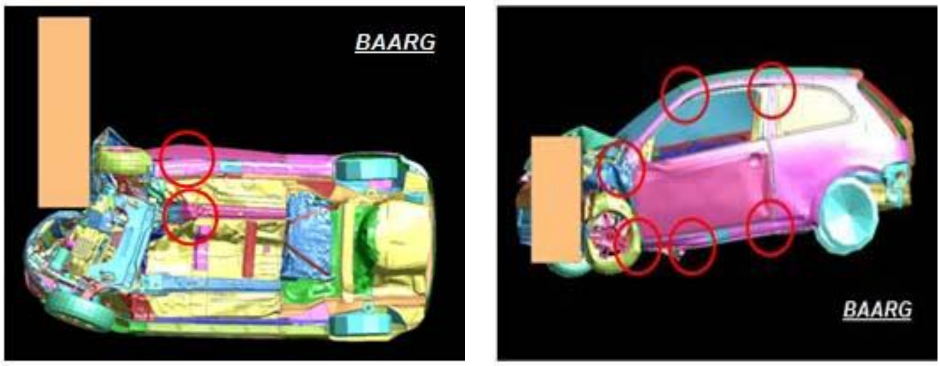
Figure 7: *Reduced material strength up to 60% showing the defect in the sill*

The results for MODE I defect in the sill show catastrophic collapse of the sill at the point of repair. This is shown in Figure 8.



a) Original Model sill performance

b) Repaired Model sill performance



c) Floor deformation

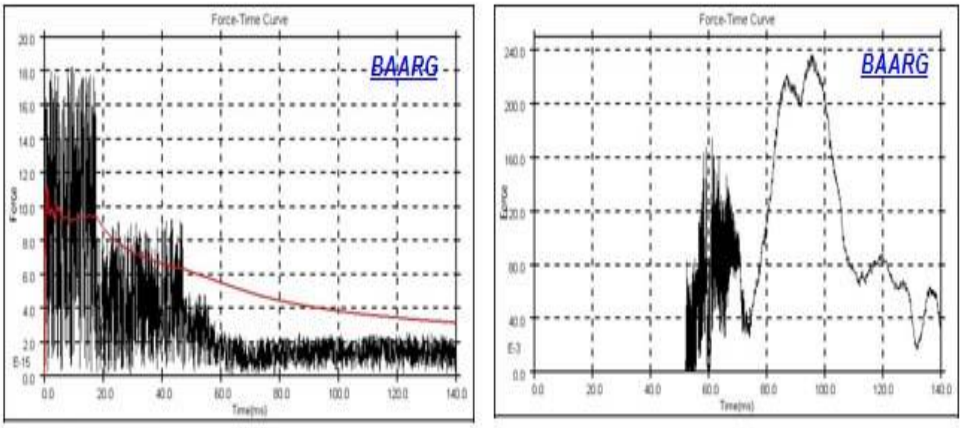
d) Side structure deformation

***Figure 8:** Original sill results compared to repaired behaviour (MODE I)*

In order to demonstrate this phenomenon, a virtual repair was done under MODE II, that signify unprofessional repair where material properties have been reduced by 60% and including the cross sectional properties. Figure 9 shows a comparison of results between the original model and that of the defected repair.

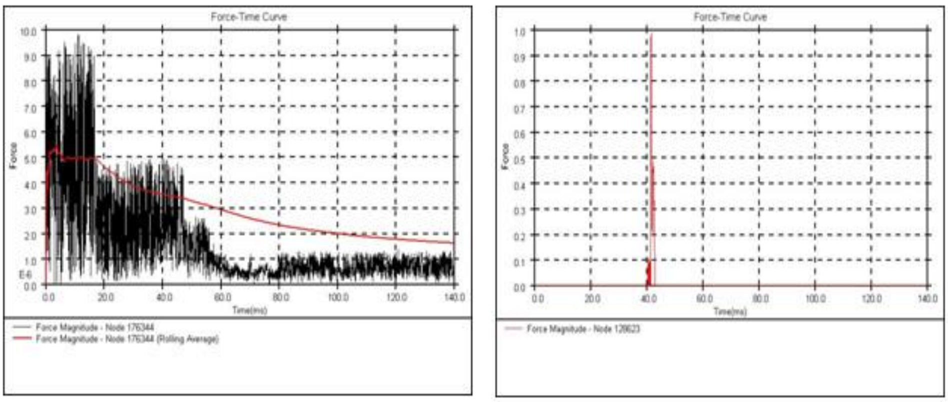
In Mode III repairs, only the cross-section properties have been reduced to reflect the unprofessional poor repair. Figure 10 shows typical results and compares them.

Once all the modes have been virtual tested it is appropriate to understand what is happening in terms of collapse mechanisms, Figure 11. The original failure behaviour indicates the collapse to be concentrated in the zone ahead of the front bulkhead. The load path is good with stresses travelling from the front to rear and over the far side. The door that has poor load carrying and transfer capability does not show high stresses. Overall the original model shows that the Ford Fiesta is a well designed car for offset frontal impact resulting in deformations to be outside the occupant safety cell.



a) Original Model sill performance b) repaired Model sill performance

Figure 9: *Original sill results compared to repaired behaviour (MODE II)*



a) Original Model sill performance b) repaired Model sill performance

Figure 10: *Original sill results compared to repaired behaviour (MODE III)*

MODE I on the other hand shows redistribution of stresses that have caused some failure to occur locally in the occupant safety zone. The failure is pronounced in MODE II and MODE III where collapse behaviour is observed. To clearly visualise this phenomenon, the rotation of the upper A-pillar with side roof rail were monitored. These are shown in Figure 12.

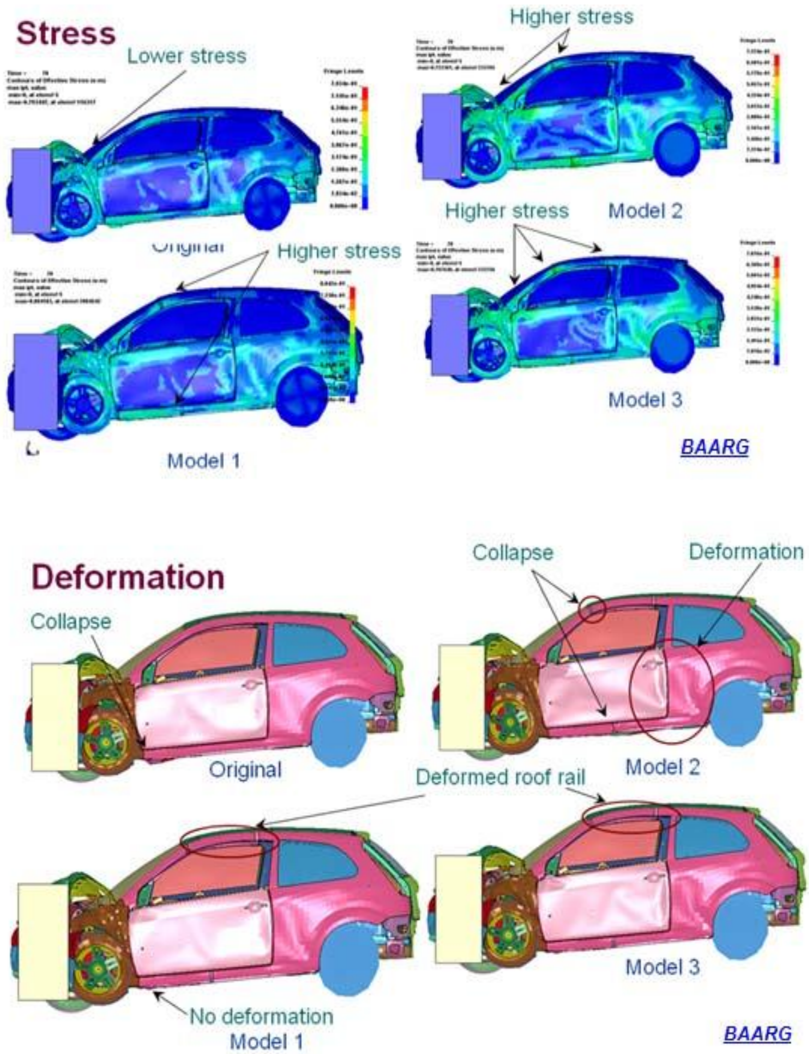


Figure 11: *von Mises stress distribution in the car body and deformation pattern*

Assessing Figure 12, it can be seen from the first glance that there are some subtle changes despite applying small defects in the structure. The original angle rate of change increases steeply in MODE II, while in MODE I falls between MODE III and MODE II, in the process showing the beginning of safety cell compartment collapse. With large defects where a big chunk of component is unprofessionally repaired, the collapse of the safety cell will follow especially under MODE II conditions. The results obtained here are in good agreement in terms of collapse mechanism and show patterns that are similar to those obtained from the experimental work.

The analysis shows that poor repair can result in high rate of angular collapse that makes the roof and side structure intrude into the occupant safety cell and thereby introduce risk to occupants.

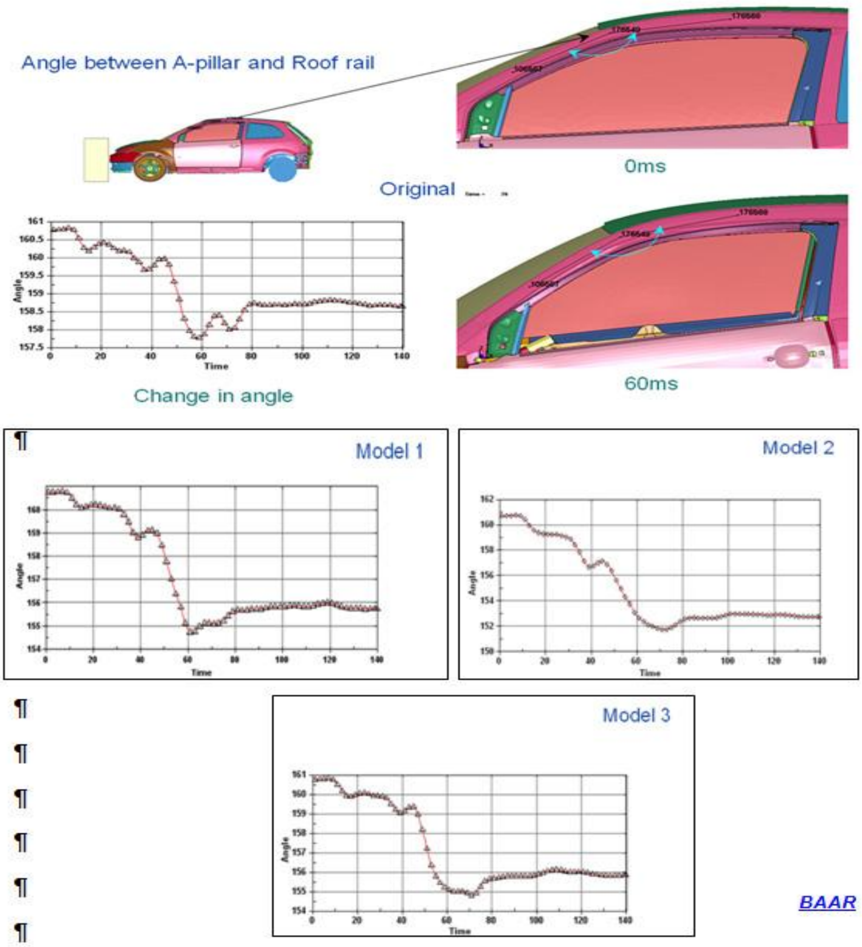


Figure 12: *The effect of joint rotation rate for the MODES I, II and III*

DISCUSSION

As a matter of principle it is possible to reconstruct a damaged vehicle even after a severe crash using state-of-the-art repair techniques and appropriate technical equipment operated by well trained staff. Whether such professional repair will be executed or not depends on the repair costs which contain labour, spare parts and varnishing. These costs have to be compared to the current replacement value of the damaged vehicle by another equivalent (used) vehicle. If the decision is not to execute a professional repair because this would be uneconomical, the damaged vehicle is a so called “total loss”.

The question is: What happens with such “total losses”, when the damaged vehicle is relatively attractive and therefore often requested on the (national or international) markets for used vehicles? Particularly for such vehicles it can be seen a real danger of nonprofessional repair with the consequence of negative impacts on quality and safety of these vehicle if they get into traffic again.

Modern cars have improved enormously in safety through using new materials to create high-resistant compartments that protect occupants. The professional repair of such vehicles having body structures built from high-strength steel, ultra high-strength steel, press-hardening steel, aluminium and its alloys, and magnesium alloys and plastics, is much more difficult than the professional repair of vehicle bodies of 10 or 15 years ago. Unless in former decades the repair of a vehicle body could be done with good results by using a universal straightening bench, blow pipes and suitable bumping hammers - and of course with good workmanship's skills - this is no longer possible in modern cars. With this background it can be stated that the risk coming from unprofessional repair has increased and will keep increasing in the future.

To cope with this matter, DEKRA together with other stakeholders have started a project "Fair Repair". Initial results presented herein show that unprofessional body repair can cause:

- failure of the structure of the vehicle body in general
- increased repair costs as a consequence of altering of deformations in low-speed crashes
- reduced safety of occupants as a consequence of reduced survival space due to a partial or total collapse of the compartment in high-speed crashes

This work on "fair repair" has yielded good results so far, and will continue with the analysis of the risks attributed to unprofessional repair. Stability and resistance of vehicle bodies will be sought in a way of finding out where the "Achilles heels" are located for different kinds of body structures or/and materials used. The results of this research will be circulated and discussed with other stakeholders in view of improving the understanding of the consequences of poor repairs.

Therefore with the knowledge gained until now, the requirements are that legal regulations for the handling of severely crashed vehicles directly after the accident, as they exist and as in use of best practice in some European countries should be mandatory all over Europe (and maybe worldwide):

- Professional repair must be done or confirmed by an accredited garage before the readmission of the repaired vehicle in participating in traffic flow.
- As an alternative, independent experts should inspect the repair process (if necessary) of the vehicle and at the end of the repair confirm the readmission of the vehicle on public roads.

This will help to assure occupant protection and save the value of vehicles after repair plus therefore maintain the highest level of safety on roads.

CONCLUSIONS

There is a positive indication that the number of bad unprofessional repaired cars involved in accidents will increase with consequences of catastrophic structural deformation and loss of occupant lives. Poorly repaired vehicles may previously have been in either side, rear, oblique, and/or frontal crashes. After panel beating them to shape, sometime there are variations in the quality of repairs, in the equipment used to do the work, in maintaining the tolerances of the original vehicle shape and geometrical parameters, and in choice of materials used.

This unprofessional attitude has negative influence on vehicle structural collapse mechanisms and should no longer be tolerated as occupant lives could unnecessarily being lost when in reality they would have survived such crashes if repairs were properly done to high quality and workmanship. In the age of new sophisticated material use and advanced production techniques employed by the OEMs, it has become increasingly important to emphasise the need to maintain quality of repairs, hence assure the survivability of occupants.

This paper has contributed to the understanding of this problem and to how it could be alleviated through employment of good workmanship that extends in sound repair of structural components, sub-assemblies and assemblies. A typical case study of a poorly repaired car in frontal 40% offset impact at 64 kph (as of Euro NCAP) with previous record of being involved in a pole-to-side-impact scenario is showing collapse modes that are compared between good and bad repair techniques through experimental and finite element analyses. The unnecessary severe collapse of the occupant compartment is evident of deteriorated safety. Numerical simulations in particular show the influence of local degradations in load paths, diminished resistance, alternate deformation characteristics and a sporadic change of stress pattern within the car body.

The assessment of possible impacts of unprofessional repairs to the safety of vehicles being driven on European roads, the occurrence and characteristics of cars damaged after real-world accidents show a problem that is growing. That is why a proposal is outlined on how to cope with today's problems of unprofessional workmanship that induce negative influences on safety, overall structural quality and long-term upholding of value.

NOTATION

$\| \Omega \|$ - Mass matrix

$\| \psi[\dot{\delta}(t)] \|$ - Damping matrix

$\| K [\dot{\delta}(t)] \|$ - Stiffness matrix

$\vec{P}(t)$ - Load vector

$\ddot{\delta}(t);\ \dot{\delta}(t);\ \delta(t)$ - Acceleration, velocity, displacement

$\| \psi * \|$ - Damping matrix of the linear part of the dynamic system

$\| K * \|$ - Stiffness matrix of the linear part of the dynamic system

$\left(\frac{\varepsilon}{\delta}\right)$ - Stored non-elastic energy per unit displacement

Δt – Time step of integration

REFERENCES

[1] Timm H, "Efficiency of Materials in Lightweight Body Design", Proceedings 10th VDA Technical Congress, Ludwigsburg, Germany, April 2-3, 2008

[2] LS-DYNA 3D, Livermore Software Technology Corporation, CA, USA, 2000

[3] A Herbst, "Optimization of finite-element physical simulations", April 2006

[4] Essig M, "Pulse welding aluminium", Search Autoparts.com, May 1, 2003

[5] I-Car Advantage, "Aluminium/steel of BMW 5 Series", 10 November 2003

[6] Mao M, Chirwa E C, "Application of Grey Model GM(1,1) to vehicle fatality risk estimation", Journal of Technological Forecasting & Social Change, Vol. 73, pp. 588 – 605, 2006.

[7] Mao M, Chirwa E C, Chen T, Latchford J, Wang G, "Numerical analysis of a small European vehicle under rollover condition", Proc. Inst. Mech. Engrs.,, J. Auto. Eng. Part D, Volume 219, No. 12, DOI: 10.1243/095440705X34946, pp. 1369 – 1380, 2005.

[8] Mao M., Chirwa E. C., Chen T., , "Vehicle roof crush modelling & validation", Proc. of The 5th European LS-DYNA User's Conference, ARUP, Paper 6c-19, International Convention centre, Birmingham, UK, 25 – 26 May 2005.

[9] Chen T., Mao M., Chirwa E. C., Wang W., Mao M., , "Side member crumple section simulation and structural optimisation", Proc. of The 5th European LS-DYNA User's Conference, ARUP, Paper 6d-45, International Convention centre, Birmingham, UK, 25 – 26 May 2005.

[10] F A Berg, P Rucker, F Leimbach, U Schmortte, E C Chirwa, G K Chinnaswamy, "The effects of unprofessional repairs on quality and safety of road vehicles subjected to crash loading", Proceedings of ICRASH 2008, Edited by E C Chirwa & H Hiroyuki, Kyoto, Japan, July 2008.