Rupture Modeling of Spot Welds Suitable for Crash FE Analysis in Vehicle Development Process

Authors:

Koushi Kumagai
Masakazu Shirooka
Jirou Ohachi
Toshirou Ogawa
Toyota Motor Corporation

Correspondence:

Koushi Kumagai
Toyota Motor Corporation
Phone +81 565 72 6115
Fax +81 565 72 6039
Email kumagai@earth.tec.toyota.co.jp

ABSTRACT:

This paper describes the development of rupture modeling of spot welds suitable for crash FE analysis in vehicle development process. The authors presented a detailed spot weld rupture model called 'spider web model' in Toyota and confirmed that it closely correlates with actual full vehicle crash test results. Although, the spider web model is accurate, extensive effort is required to construct the model. Also, the spider web model can only simulate the nugget pullout mode of spot weld rupture and it cannot simulate the nugget fracture mode observed in the ultra high strength steels. Many investigations have been conducted on spot weld rupture modeling using mesh free connection which is suitable for vehicle development process. However, these models have not been validated with a full vehicle level test results.

A spot weld rupture model using beam element and mesh free connection, which can simulate both nugget pullout and nugget fracture mode of spot weld rupture, has been developed. Full vehicle level FE analysis is conducted to confirm the prediction accuracy of developed spot weld rupture model. Results show that spot weld rupture locations and number of ruptured spot welds closely correlate with actual crash test results.

Keywords:Spot Weld, Rupture, Crash, Steel

1.Introduction:

Body-In-White structure of a vehicle mainly consists of hundreds of fabricated sheet metal parts joined with spot welds. Spot welds can rupture during crash testing as the body is deformed and the crash energy is absorbed. Therefore, in order to accurately estimate the crash deformations in FE analysis, it is important to simulate spot weld rupture.

The authors have already reported FE analysis using a detailed spot weld rupture model called 'spider web model' that closely correlated with actual crash testing, in which number of spot welds were found to be rupturing [1]. However, the spider web model requires extensive modeling, making it is impractical for vehicle development process. Also, it can only simulate the nugget pullout mode of spot weld rupture and it cannot simulate the nugget fracture mode observed in ultra high strength steels.

Many spot weld rupture models based on beam or solid elements which use mesh free connections have been reported [2]. Although, these models are suitable for vehicle development process, they have not been validated with actual crash tests in which actual spot welds rupture.

2.Development of spot weld rupture model:

2.1. Investigation of spot weld rupture modes

2.1.1. Development of a detailed model for investigating rupture modes

A detailed model consisting of solid elements shown in Fig 1 is developed to investigate two rupture modes of spot welds and the mechanism of branching into these modes.

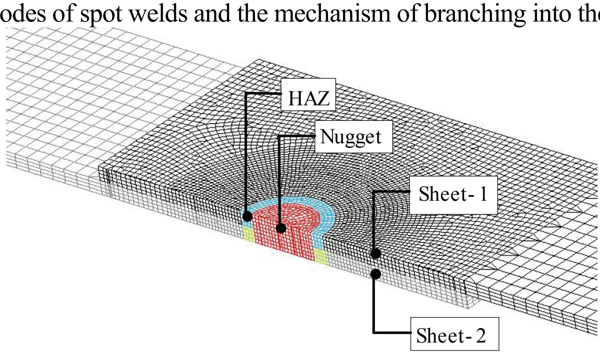

Fig.1 Detailed spot weld model using solid elements

Material properties of nugget and heat affected zone (HAZ) around the nugget are identified considering the hardness distribution in these regions according to a method similar to that reported by Werner et al [3]. Lap-shear specimens with minimum and maximum nugget diameters, which show distinct nugget fracture and nugget pullout modes respectively in test, are considered. The reason for selecting the lap-shear specimen is that,the rupture mode changes from nugget pullout to nugget fracture depends on nugget diameter. The rupture modes obtained from the FE analysis are shown in figure 2 and 3. These rupture modes correlate with the rupture modes observed in test for corresponding nugget diameters.

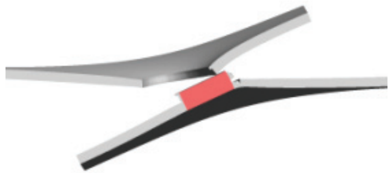

Fig.2 Nugget pullout mode - FE analysis (max. nugget diameter)

Fig.3 Nugget fracture mode - FE analysis (min. nugget diameter)

The time histories of ratios of loads obtained from FE analysis to maximum loads in test for respective cases are shown in figure 4. Figure 2 to 4 show that the rupture mode and rupture load closely correlate with the test results regardless of nugget diameter.

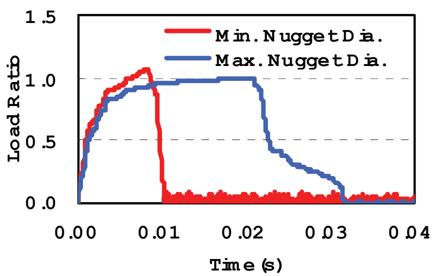

Fig.4 Ratios of loads obtained from FE analysis to maximum load in test.

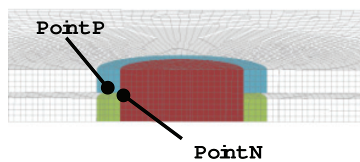

Fig.5 Rupture initiation points of nugget pullout and nugget fracture

2.1.2. Investigation of rupture modes and branching mechanism

Rupture modes are investigated in detail using results of the developed model. The point of rupture initiation is closely examined for both modes. Results show that the rupture initiation point is different in each mode. These points, P for nugget pullout mode and N for nugget fracture mode, are shown in figure 5.

The ratio of plastic strain at point P and N to critical rupture strain in each case is shown in figure 6. When the strain ratio at either P or N reaches a critical value 1.0, rupture initiates at that point. In case of maximum nugget diameter, the strain ratio at point P is greater and reaches the critical value earlier than that at point N. Therefore, the rupture occurs due to nugget pullout mode. On the other hand, in case of minimum nugget diameter, the strain ratio at point N is greater and reaches critical value earlier than that at point P. Therefore, the rupture occurs due to nugget fracture mode.

Furthermore, the rate of change of strain ratio at point P is almost same regardless of nugget diameter. But the rate of change of strain ratio at point N is greater in case of minimum nugget diameter and smaller in case of maximum diameter. Therefore, in case of minimum diameter, the strain ratio at point N reaches the critical value earlier than that at point P. This causes the branching into nugget fracture mode in case of minimum diameter. On the contrary, in case of maximum diameter, the strain ratio at point P reaches the critical value earlier than that at point N. This causes the branching into nugget pullout mode. These observations reveal that the branching into two modes of spot weld rupture depends on the critical strain and the rate of change of strain at the point of initiation of rupture in respective modes.

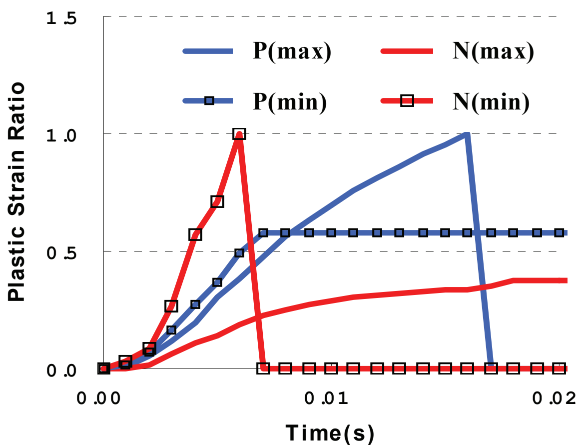

Fig.6 Ratio of plastic strain to critical strain at point P and N

2.2. Development of a spot weld rupture model suitable for vehicle development process

2.2.1. Basic structure of the model

The spot weld model using beam elements and mesh free connections, which is practicable for full vehicle crash analysis, is thought to be a suitable model for vehicle development process. This model does not require any additional modeling effort compared to other current mesh free models. The rupture prediction is based on forces in beam elements and rupture is simulated by elimination of beam element upon reaching the rupture criterion.

2.2.2 Rupture functions

The rupture initiation is predicted using rupture functions derived from results explained in section 2.1.2. Two rupture functions have been derived to predict the rupture initiation in two different modes. The rupture function Fp, expressed in equation (1) predicts the rupture initiation in nugget pullout mode, whereas the rupture function Fn, expressed in equation (2) predicts the rupture initiation in nugget fracture mode. The rupture is considered to initiate when the value of any of these two rupture functions reaches 1.

$$F_p = \frac{\left(C_{11} \bullet F_a \big/ D^{n11} + C_{12} \bullet M \big/ D^{n12} + C_{13} \bullet F_s \big/ D^{n13}\right)}{\sigma_{pf}\left[1 + \left(\dot{\varepsilon}/C\right)^{1/p}\right]} \tag{1}$$

$$F_n = \frac{\sqrt{\left(C_{21} \bullet F_a + C_{22} \bullet M\right)^2 + 3\left(C_{23} \bullet F_s\right)^2}}{D^{n2}\sigma_{nf}\left[1 + \left(\dot{\varepsilon}/C\right)^{1/p}\right]} \tag{2}$$

Fa: Axial force in beam element
Fs: Shear force in beam element
M: Bending moment in beam element
D: Diameter of nugget

C11,C12,C13: Coefficients in nugget pullout function
n11,n12,n13: Nugget dia. exponents in nugget pullout function
σpf: Critical stress in nugget pullout mode
C21,C22,C23: Coefficients in nugget fracture function
n2: Nugget dia. exponent in nugget fracture function
σnf: Critical stress in nugget fracture mode
C,p: strain rate parameters

2.2.3. Procedure to predict the branching into two rupture modes

A procedure has been developed to predict the branching into two rupture modes. According to this procedure, two rupture functions Fp and Fn are calculated at all possible points of rupture initiation. For example, points Pp1 and Pp2 shown in figure 7 are two possible points for rupture initiation in nugget pullout mode. Similarly, points Pn1 and Pn2 shown in figure 7 are two possible points for rupture initiation in nugget fracture mode.The rupture mode and rupture initiation point are determined by following inequality expression

(3).

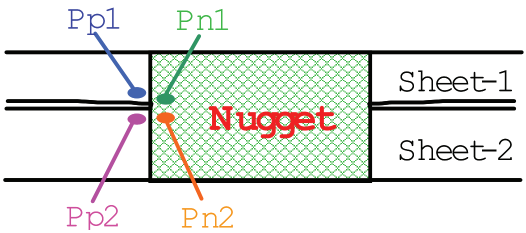

Fig.7 Schematic drawing of rupture initiation points

$$\max(F_{pp1}, F_{pp2}, F_{nn1}, F_{nn2}) \geq 1 \qquad (3)$$

F_{pp1}: Value of rupture function Fp calculated at point Pp1
F_{pp2}: Value of rupture function Fp calculated at point Pp2
F_{nn1}: Value of rupture function Fn calculated at point Pn1
F_{nn2}: Value of rupture function Fn calculated at point Pn2

2.2.4. Introducing damage function

Sudden elimination of spot weld element upon reaching the rupture initiation criterion causes a surge in loading of neighboring spot welds due to transfer of load. This causes increased propagation of spot weld rupture. A damage function similar to that suggested by Seeger et al [2] is introduced to prevent the increased propagation of spot weld rupture. Introduction of damage function gradually reduces the resistance of spot weld from rupture initiation to the final tearing of spot weld. The damage function expressed in equation (4) is derived considering the test results. This damage function is used to scale the stresses in spot weld element as expressed in equation (5). The spot weld beam element is eliminated when the plastic strain reaches the rupture strain.

$$d = \left(\varepsilon^{p} - \varepsilon^{p}_{fini}\right) / \left(\varepsilon^{p}_{rup} - \varepsilon^{p}_{fini}\right) \qquad (4)$$

$$\sigma_{d} = \sigma \exp(-\beta d) \qquad (5)$$

d:damage
ε^{P} , :Plastic strain in beam element
ε^{P} , fini:Plastic strain in beam element at rupture initiation
ε^{P} , rup:Critical plastic strain of beam element

σ:Stress in beam element
σd:Stress in beam element after rupture
β:Decay coefficient

2.3. Identification of

parameters

The parameters of rupture functions given in equation (1) and (2) are identified for each thickness and material combinations. Material ranging from 270 to 980 MPa class of steels and the thickness ranging from 0.8 to 2.3mm are considered for parameter identification. Parameters are identified by validating with test results for combination of 3 types of specimens and 3 types of nugget diameters.

2.4. Results of validation

Results of validation for 1mm thickness 270 MPa class of steel are shown in figure 8. The rupture load estimation error is within 10% for 3 specimen type and 3 nugget diameter combinations. Also, the rupture modes correlate with test results in all combinations. Results of validation for 1mm thickness 980 MPa class of steel are shown in figure 9. Again the rupture load estimation error is within 10% for 3 specimen type and 3 nugget diameter combinations. In these cases also, the rupture modes correlate with test results.

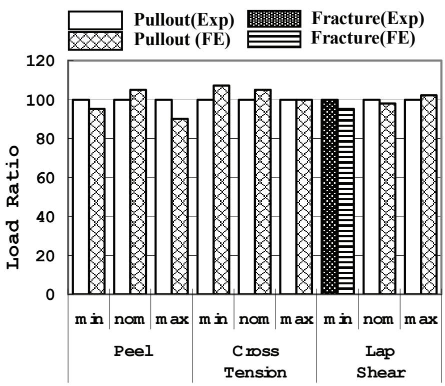

Fig.8 Accuracy of estimated rupture loads and mode for 1.0mm of 270MPa

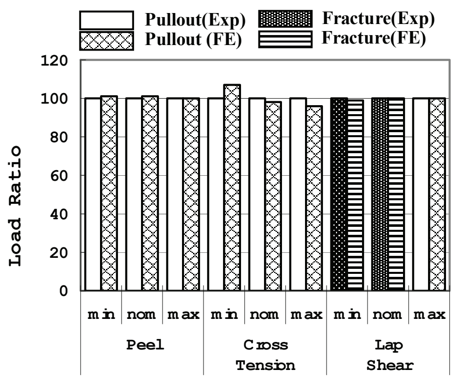

Fig.9 Accuracy of estimated rupture loads and mode for 1.0mm of 980MPa

2.5.Validation with 3-sheet spot weld specimen composed of different thickness

The test configurations used for validation to identify parameters consisted of only 2-sheet weld joints with both sheets having same thickness. But the Body-In-White structures contain spot welds with various thickness combinations and about 30% of welds are 3-sheet weld joints. A spot weld rupture model validated with only 2-sheet welds with both sheets having same thickness may not be able to predict the rupture in Body-In-White structure with sufficient accuracy.

Therefore, the developed spot weld rupture model is validated with specimens composed of 3 different sheets thickness as shown in figure 10. The ruptured shape of 3-sheet weld test specimen is shown in figure 11. The rupture is occurring by nugget pullout from sheet 3. Figures 12 and 13 show the results of developed model. As shown in figure 12, the spot weld ruptures between sheet 2 and 3 but the rupture mode isn't distinguished. As shown in figure 13, the spot weld ruptures when the value of rupture function for nugget pullout at sheet 3 reaches the rupture criterion. This shows that, the developed spot weld rupture model can accurately predict the rupture not only in joint configurations with 2 sheets having same thickness but also in those with 3 sheets having different thickness combinations.

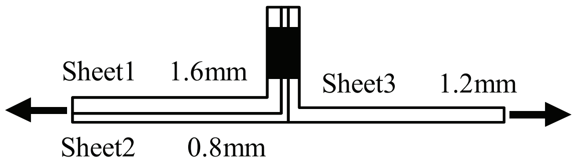

Fig.10 Section of specimen including 3 sheets spot weld

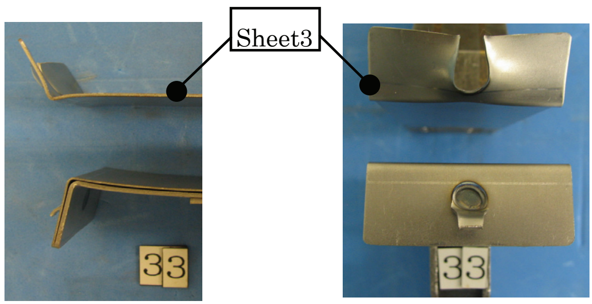

Fig.11 Ruptured shape of specimen including 3 sheets spot weld

Fig.12 Ruptured shape of FE analysis results

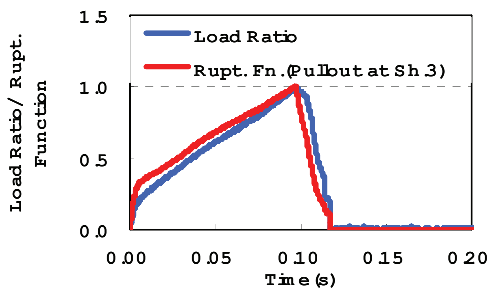

Fig.13 Estimated rupture loads and rupture function value at sheet 3 for nugget pullout

3. Validation with full vehicle crash test:

3.1. FE model for validation

A full vehicle FE analysis is conducted to confirm the accuracy of the developed rupture model. Rear impact analysis according to FMVSS 301 test conditions is carried out. The model used for FE analysis is shown in figure 14. About 800 spot welds in the rear part of Body-In-White are modeled in the developed rupture model, shown by red dots in figure 15.

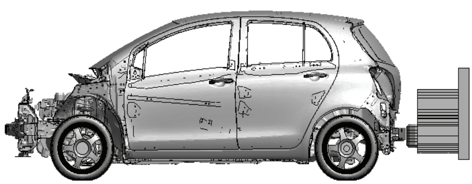

Fig.14 Full car model for rear impact testing

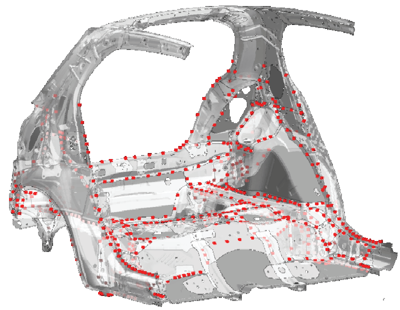

Fig.15 Modeled spot rupture model in rear part of body

3.2. Results of FE analysis

The predicted number of ruptured spot welds in FE analysis is compared with the test results is shown in table 1. Ruptured spot welds in test are counted based on visual observations. Table 1 shows that the number of ruptured spot welds in FE analysis correlates with the test results.

Table 1 Comparison of number of ruptured spot welds between test and FE analysis

	Test	Analysis
Number of Ruptured Spot Welds	56	49

A comparison of the number of ruptured spot weld and location of rupture is made between FE analysis results and the test results at various locations where extensive rupture is observed in test. Figures 16 and 17 show the results of the test and FE analysis respectively at the rear left wheel housing. At this location, 10 welds are ruptured in the test, which are accurately predicted by FE analysis.

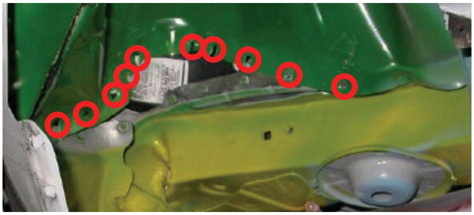

Fig.16 Ruptured spot welds at wheel housing in the test

Fig.17 Ruptured spot welds at wheel housing in FE analysis

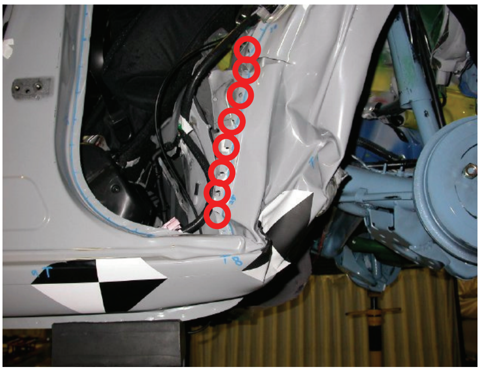

Fig.18 Ruptured spot welds at left rear door opening in the test

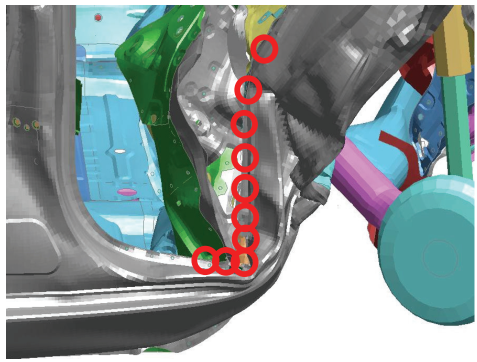

Fig.19 Ruptured spot welds at left rear door opening in FE analysis

Fig.20 Ruptured spot welds at right rear door opening in the test

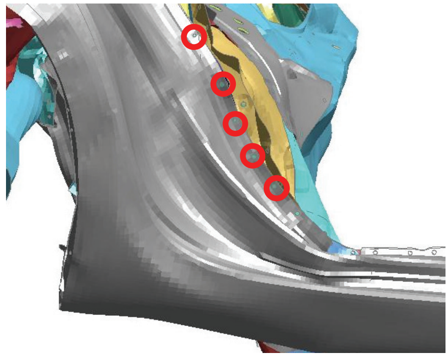

Fig.21 Ruptured spot welds at right rear door opening in FE analysis

Figures 18 and 19 show the test results and FE analysis results respectively at rear left door opening. The number of spot welds ruptured in the test is 8 whereas the number of ruptured spot welds predicted by FE analysis is 10.

Figures 20 and 21 show the test results and FE analysis results respectively at the rear right door opening. At this location, 6 spot welds are ruptured in the test whereas 5 spot welds are predicted as ruptured in FE analysis. These results show that, the location and number of ruptured spot welds predicted by FE analysis closely correlate with test results.

4. Discussion:

4.1. Physical meanings of rupture functions

The reason for closer correlation between test results and the developed force based rupture model is explored in this section.

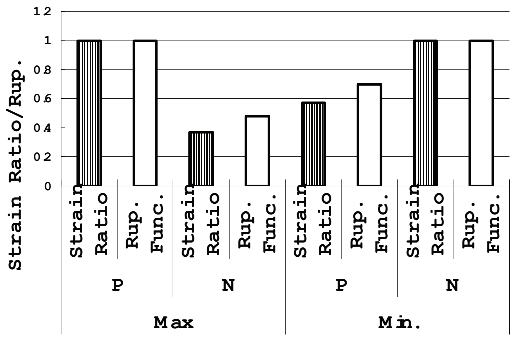

Fig.22 Comparison of strain ratio and rupture function

value at rupture initiation

In principle, a spot weld ruptures when the plastic strain in or around nugget reaches the critical strain. The spot weld rupture can be accurately predicted if the plastic strain can be estimated. On the contrary, the developed rupture model is based on spot weld beam element forces and it cannot estimate the plastic strain directly. Therefore, the relationship between plastic strain and rupture function value is investigated.

The ratio of plastic strain to critical strain and rupture function value at point P and N at the time of rupture initiation for maximum and minimum diameter cases of same specimen are shown in figure 22. The rupture function value closely correlates with the strain ratio in each case. These observations show that the rupture function indirectly estimate the strain ratio. Therefore, it is thought that the results obtained by the developed spot weld rupture model correlates with actual crash test results.

5. Conclusions:

(1) A detailed spot weld model has been developed to understand the nugget pullout and nugget fracture modes of spot weld rupture.

(2) Based on the investigation using detailed model, the mechanism of branching into two rupture modes is revealed.

(3) A spot weld rupture model based on beam elements with mesh free connections, suitable for vehicle development process, is developed considering two rupture modes. The developed rupture model has been validated with test results of steels ranging from 270 to 980MPa classes.

(4) It has been confirmed that the developed model correlates with the specimen level test results including 3-sheets welds having different thickness combinations.

(5) Also, the developed model is found to predict the rupture location and number of ruptured spot welds in a rear impact test.

Acknowledgements:

The authors acknowledge the contribution of Nippon Steel Corporation to the test results. The cooperation of Dr. Lee Bindeman and Dr. John O. Hallquist of Livermore Software Technology Corporation, Prof. David J. Benson of Mechanics at University of California at San Diego and Dr. Mitsuhiro Makino of Fujitsu Limited in implementation of spot weld rupture model in LS-DYNA is greatly appreciated. The support of Mr. Kumbar Somaling of Trans Cosmos Inc. and Mr. Masahiro Nakagami of Toyota Technical Development Corporation in the validation of spot weld rupture model is greatly appreciated.

References:

[1] Kumagai et al.: "Rupture Modeling of Spot Welds under Dynamic Loading for Car Crash FE Analysis" JSAE Technical Paper No. 200065658

[2] Seeger et al.: "An Investigation on Spot Weld Modeling for Crash Simulation with LS-DYNA", Proceedings of 4th LS-DYNA forum 2005(2005)

[3] Werner et al.: "CrachFEM-A Comprehensive Failure Model for Metallic Structures in Sheet Metal Forming and Crash Simulation", Proceedings of EuroPAM 2004