The role of plasticity in the integrated approach of subsequent simulations of car structures

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ABSTRACT: In the development of car structures the performance (i.e. dynamic behavior, fatigue life) is analyzed by prototype testing and simulation. Nowadays, the simulations are based on the geometry that is obtained directly from the CAD construction. It is known however, that forming can change the material performance considerably. To improve the accuracy of the virtual model the irreversible effects of the forming operations must be integrated by means of coupling the successive operations in a virtual process chain. Therefore all previous forming and joining steps must be evaluated and results must be transferred to the next step. Opposite to standard models now the real thickness of sheet metal parts and residual stresses due to forming and joining and the changed material parameters at every point are known prior to applying any service loads. This results in a more reliable prediction of product performance. In this paper it is demonstrated how the performance of chassis parts changes with the inclusion of plastic forming effects compared to neglecting them. This involves the transfer from results of the forming process to the comprehensive model. The joining to (sub-)assemblies of the different parts is included in a parameterized way. Hereafter the model will be subjected to static and dynamic external loads and compared to calculations using a standard model. The results clearly show that the inclusion of the plastic history has a significant influence on the product performance.

Key words: process chain, virtual prototyping

1 INTRODUCTION

The trend in automotive industry is more and more towards lightweight construction. Therefore a compromise must be found between the weight and the function of the part. This is especially true for structural parts which do not only have to deliver static and dynamic stiffness but also have to offer crash safety. In the case of chassis parts further restrictions are given by a minimum safe-life and the package design. Furthermore, the weight of the undampened masses is critical. It is well known that the yield stress of steel increases in the deep drawing process. There are also strong indications that the fatigue life is improved due to the plastic strain that the material encounters during the deep drawing process [1]. Additional to this positive effects the deep drawing gives a diminished thickness of the sheet thus reducing the static stiffness and adding residual stresses. To raise the quality of the virtual models the simulation of the whole development process must become as exact as possible. On the other hand there is a strong demand for shortening the development cycles considerably. To unify these two goals it is necessary to integrate the complete manufacturing process in the performance analysis. In this paper the general procedure to include the effects of plasticity in subsequent simulations is discussed. It is illustrated with an example. The paper closes with an overview of future research and suggests which developments should be prioritised.

2 INTEGRATED APPROACH

Part production in the automotive industry generally involves the plastic deformation of the basic
material, e.g. casting, bulk forming or sheet forming like deep drawing or hydroforming. In this paper we will restrict ourselves to deep drawn parts only. Nowadays, the deep drawing process is well-understood and the simulations yield results of satisfactory quality. After drawing a series of operations are performed needed to come to the final assembly.

2.1 Simulation chain

Since the material state is changed by every step in the production process, the behaviour of the final part will depend on each of these steps. Until now, this is not considered in standard simulation for the structure (static and dynamic analysis), fatigue life and crash. For obvious reasons the integration of the plastic history from forming and assembly will therefore lead to an improvement of the quality of the virtual product testing. Figure 1 shows the subsequent steps that have to be performed to realise this.

![Fig. 1. The virtual processing chain](image)

Starting point is the CAD construction defining the geometry of the part which has to meet the requirements on package geometry. Together with the basic material properties this gives the basis of the forming simulation. After deep drawing the thickness, the material properties and the stress state have changed. In the subsequent joining of single parts to complex sub-assemblies a significant but unwanted effect on the geometry as well as the stress state arises. The detailed simulation of joining, e.g. welding or riveting, is expensive. Therefore the properties of the joints have to be included in a parameterised way. The result is a virtual model, which includes the complete plastic history. For every point the material state variables and stress state are known now. These new kind of highly detailed models allow for a more accurate prediction of product performance, such as crash, fatigue and structural behaviour. They can also improve the elastic multi-body-simulation (MBS).

2.2 Joining models

After positioning of the different parts they will be joined to a structure. The deformations and stresses that come into being due to riveting or welding must be incorporated in the model. For reasons of CPU time the joint cannot be modelled very detailed. Therefore simplified models that contain its characteristic properties are developed.

![Fig. 2. Shear tensile test of a spot weld, measurement and simulation](image)

For spot welding and riveting a moderate local refinement is sufficient to get a unified behaviour for every joint. Via numerical experiments the stiffness of the joint is determined such that its experimental behaviour is approximated in the FE-model. For seam welds the local residual stress due to welding is much more important than the elastic behaviour. These stresses are the reason for the welding distortion. In welded structures they must be incorporated in the subsequent calculations.

2.3 Data chain

Forming simulations usually need a very detailed and fine mesh in order to obtain the demanded accuracy. In subsequent simulations of the assembly these fine meshes would lead to large CPU times. Therefore the results of the forming simulation are transferred to a coarse mesh which is based on the CAD construction. Unfortunately, this process unavoidably loses valuable information. Either the integral forces and stresses are in equilibrium and peaks will get lost or the peak values are maintained but inner and outer forces are out of equilibrium. A simple but acceptable third way is implemented here: the state variables of the integration points in
the new mesh get the values of the nearest integration point in the old mesh. It is desirable to use consistent data in the application of the process coupling as proposed in this paper. This means that for every simulation all effects from previous steps are taken into account. For example, it can be misleading to regard solely the hardening resulting from deep drawing. The thinning of the material has a contrary effect on the strength and could outweigh the effect of hardening.

3 EXAMPLE: UPPER SHELL OF A STEERING KNUCKLE

As an example of the discussed method the upper shell of a steering knuckle is considered, see figure 3. It is deep drawn from thick steel sheet (St14, 2 mm), in one stage.

![Fig. 3. Upper shell of a steering knuckle – tools and calculated thickness with INDEED](image)

### 3.1 Static strength

After the deep drawing process the part is trimmed and subsequently unloaded. The state variables of the material, thickness and the residual stress after springback are now mapped on a typically coarse mesh in a program for structural calculations, here ABAQUS. The result is shown in figure 4.

![Fig. 4. Transfer of the total plastic strain to the coarse mesh](image)

The transfer of the total plastic strain is required to ensure that the onset of yielding in the structural calculation is correct. Next a load case is defined that is typical for the in-service behaviour of this part.

![Fig. 5. Simulated load-displacement curves with and without plastic history](image)

Figure 5 shows load-displacement curves obtained with and without integration of plastic history. It can be easily seen that the inclusion of the forming history has a significant effect on the strength of the part. The deviation is about 30 percent, which is not unusual in practice when comparing standard simulations (without history) with experiments. Therefore, the inclusion of plastic history in these type of calculations is expected to give an improvement of the quality of the predictions.

### 3.2 Fatigue life

Next to structural calculations also fatigue-life calculations are standard in product development. The considered part is analysed with FEMFAT with and without the inclusion of plastic history. It is based on the ABAQUS geometry and history of figure 4. This means that thickness, total plastic strain and stresses are taken into account. According to some authors the fatigue life increases with the amount of total plastic strain [1,2]. Figure 6 illustrates this for steel St14 (DC04).
With increasing strain both the fatigue limit and the maximum number of load cycles under a given load increase. This indicates that a pre-deformation has a positive effect on the fatigue life.

Figure 7 shows the simulated damage distributions with and without the inclusion of the plastic history. In the critical region the amount of damage has decreased clearly compared to standard calculations. For the industry this would mean that parts might be constructed with thinner sheet. Nonetheless, care should still be taken.

4 FUTURE RESEARCH

Measurements on real parts have to be made in order to verify the results of this research. For an accurate prediction of the fatigue life of assemblies more data on the basic materials is required. Concretely speaking, these are the S/N curves for different pre-deformations. A follow-up step in the current research would be simplified models for seam welds. Since seam welding is the most important joining technique for chassis parts, these models allow for the complete simulation from forming to virtual testing with the inclusion of the plastic history. Given the appropriate interfaces, the forming history can be considered in crash simulations, see [4]. A final step could be the inclusion of deviations between CAD and actual geometry as a result from springback. This would have an effect on the mapping procedure and on the assembly. Parts that are to be joined must be loaded to enable the joining procedure. This results in extra assembly-stresses that can have a significant influence on the product’s performance.

5 CONCLUSIONS

With the help of an example it is demonstrated in this paper how the inclusion of the plastic history of parts affects the product performance with respect to strength, fatigue life and crash. This involves the transfer of the total plastic strain, the thickness change and the residual stresses from deep drawing and joining to the typically coarse meshes used for static and dynamic analysis. Then the product is ready for the virtual test. As an example of this method the upper shell of a steering knuckle was used for a static and fatigue life calculation. Both results were compared with the ones gained through the exclusion of plastic history. Generally speaking, the accuracy of the performance predictions will increase. With the coupling of the virtual production processes and the virtual prototypes presented in this paper the virtual process chain is closed. This leads to a reduction in cost and development times.

ACKNOWLEDGEMENTS

Volkswagen Braunschweig is greatly acknowledged for providing the data of the part.

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