Results verification of numerical simulation of the side impact of a vehicle in a three-point bending test

E Evin¹, S Nemeth²
¹ Department Automotive production, Faculty of Mechanical Engineering, Technical University of Košice, Slovak Republic
² U.S.Steel, Research and Development, 044 54 Košice, Slovak Republic
Emil.Evin@tuke.sk and SNemeth@sk.uss.com

Abstract. The research objective was to use numerical simulation to verify safety characteristics of deformation zone reinforcements subjected to bending, obtained from experimental results of the stretch-bending test. The methodology proposed for result verification by means of numerical simulation using a three-point bending test was verified on a sheet metal strip made of micro alloyed steel H 220 PD and a two-phase ferritic-martensitic steel DP 600. Material data for the material model according to Krupkovsky were determined in the tensile test. The measured data were processed tabularly and graphically. A comparison of the deformation work constant and the stiffness and deformation force constants shows that a very good match between the measured and the calculated characteristics has been achieved. Based on the data obtained, it can be assumed that it is possible to reduce the weight of deformation elements while maintaining the required safety characteristics by replacing micro alloyed steel H 220PD with the two-phase DP steel.

1. Introduction
Raising car safety standards is crucial when it comes to developing solutions for the automotive industry. Traffic collision analyzes show that in more than 60% of cases, it is the front car parts that are damaged, in more than 25% of cases, parts of the vehicle are damaged in a side impact and in about 14% of cases, it is the rear parts of the vehicle that sustain damage. [1,2,3] The above-mentioned data on car collisions point to the fact that it is necessary to focus primarily on safety measures linked to safety deformation zones in the front and the side parts of car bodies. Structural safety features in vehicles are designed to control redistribution of deformation forces in a collision so that part of the energy directed to the passenger cabin is distributed outside this cabin. When a deformation element is compressed or bent, the time required for the vehicle to come to a complete stop is extended. According to Newton’s second law

\[ F_{AVG} \Delta t = m \Delta v \] (1)

this results in a lower change in momentum and a reduction in the effect of the forces acting on the passengers. The primary function of deformation zones elements is to absorb the energy of the impact and the secondary function is to prolong the time necessary for the vehicle to stop after such impact. Deformation parts located in the front and rear of the vehicle are made of several types of materials capable of gradual absorption of a greater amount of energy directed into the passenger cabin during the impact over a longer distance. Therefore, the parts of the passenger cabin are made of high-strength...
materials, which are able to absorb a certain amount of energy directed into the passenger cabin over a short deformation path and, thus, eliminate the transmission of impact forces to the passengers [4,5]. In the event of a side impact, serious injuries to passengers occur, of which up to 35% result in death of the passenger. The severity of traffic collisions consequences in a side impact is to some extent also related to the length of the deformation zones in the door area. In this area, the length of the deformation zone ranges from 100 to 200 mm, while the length of the deformation zone in the front part of the vehicle is between 300 and 1200 mm. The role of the deformation elements structure in the door is to strengthen the door and dissipate the impact energy. The reinforcements in the door are slightly bent outwards from the vehicle so that in the event of an impact, part of the impact energy is absorbed by the door frame.

Figure 1. Reinforcement applications in deformation zones [6]

As the number of different types of cars increases, so does the need to assess their safety. There are currently several independent organizations in the world (Euro-NCAP, ASEAN NCAP, Global NCAP) that analyze and evaluate vehicle safety in accordance with their rules and standards. However, the results of test evaluations performed by individual organizations often vary. The efficiency of testing different configurations of collision situations using physical vehicle-barrier crash tests is very low. A more effective solution are numerical simulation applications that make it possible to replace physical impact tests. Numerical simulation programs LS DYNA, PAM CRASH, etc. make it possible to predict a vehicle's behavior in the event of a collision and the effects of the collision on the vehicle crew. Based on the simulations results, carmakers can test vehicle designs without creating a real vehicle model, saving production preparation time and the associated costs. The simulation results accuracy depends on the material model used, the geometry of the components, etc. [7,8]. In order to achieve the greatest possible match between the results obtained from physical models and the results obtained in a numerical simulation, the material models must reliably describe the behavior of the parts in the event of a traffic collision. Linear and nonlinear material models are used in numerical simulation - figure 2 and figure 3. Defining the material model in FEM software is done within the so-called preprocessing. In addition, this phase also includes the preparation of a geometric model, a load model, and the definition of limit condition[9,10,11].
2. Experimental research methodology

To verify the results obtained in numerical simulation of three-point bending of sheet metal strips, sheets made of high-strength two-phase ferritic-martensitic steel DP 600 and micro alloyed steel H220PD were used for experimental research, the chemical composition of which is given in Tab. 1.

Table 1. Chemical composition of the materials used

| Material | Chemical composition % |
|----------|------------------------|
|          | C  | Si  | Mn  | P   | S   | Cu  | Al  | Cr  | Mo |
| H220PD   | <0.077 | 0.019 | 0.358 | 0.011 | <0.002 | 0.017 | 0.026 | 0.009 | <0.007 |
|          | Ni | V   | Ti  | Nb  | Co  | W   | Fe  |
|          | <0.002 | 0.003 | <0.002 | 0.031 | 0.017 | <0.036 | 99.38 |
| DP 600   | <0.111 | 0.279 | 1.963 | 0.026 | <0.002 | 0.019 | 0.031 | 0.206 | <0.002 |
|          | Ni | V   | Ti  | Nb  | Co  | W   | Fe  |
|          | <0.002 | 0.012 | <0.002 | 0.02  | 0.017 | <0.005 | 97.31 |

H220PD is a fine-grained micro alloyed steel with a ferritic structure. Secondary admixtures of nitrides and carbides are present in the microstructure of the base material - figure 4. The structure of two-phase steel DP 600 is formed by a ferritic matrix and disperse fragments of martensite in this matrix - figure 5. The data required to model the materials were obtained in tensile tests done in compliance with STS EN 10 002-1, EN ISO 10275: 2020-12 - in table 2.
Figure 4. Microstructure of H220PD steel base material

Figure 5. Microstructure of DP 600 steel base material

Table 2. Mechanical properties

| Material | Rp0.02 [MPa] | Rm [MPa] | Ag [%] | A80 [%] | K [MPa] | n0.05 | sd,ov,T [MPa] | Wpl [Nm] |
|----------|--------------|----------|--------|---------|---------|-------|---------------|---------|
| H220PD/STDEV | 388          | 648      | 17.6   | 28.2    | 728     | 0.179 | 465           | 113     |
| DP600/STDEV | 372          | 632      | 19     | 28      | 1075    | 0.21  | 329           | 168     |

In the event of a frontal and side collision of a vehicle with an obstacle, the reinforcements are subjected to bending stresses. A three-point bending test, in combination with a stretch, was used to model the bending force stress of the longitudinal crossbars and reinforcement in the door - figure 6.

Figure 6. Tool layout on the TIRAtest 2300 tearing machine

Testing was performed on a TIRATEST 2300 tearing machine on specimens with a width of 38 mm, a length of 300 mm and a thickness of 0.77 mm. The speed of the bender was set at 10 mm/min. The specimens were placed on support rollers and their ends were attached firmly to remain under the holder when they are deformed by the bending force, instead of being pulled out. The bending force
was recorded with the help of sensors depending on the path. Values measured for the bending force, path, are given in table 3.

### Table 3. Measured data from stretch-bending test

| Material | Experimental results | Results obtained by simulation |
|----------|-----------------------|---------------------------------|
|          | $F_{B \text{ max}}$  |
|          | $[kN]$                |
|          | $x_{\text{max}}$     |
|          | $[mm]$                |
|          | $W_{\text{pl}}$      |
|          | $[Nm]$                |
|          | $C_{\text{pl}}$      |
|          | $[N/m]$               |
|          | $F_{B \text{ max}}$  |
|          | $[kN]$                |
|          | $x_{\text{max}}$     |
|          | $[mm]$                |
|          | $W_{\text{pl}}$      |
|          | $[Nm]$                |
|          | $C_{\text{pl}}$      |
|          | $[N/m]$               |
| DP600    | 18,03                 |
|          | 36                    |
|          | 651                   |
|          | 0,502                 |
|          | 18,031                |
|          | 36                    |
|          | 669                   |
|          | 0,516                 |
| H220PD   | 14,12                 |
|          | 38                    |
|          | 528                   |
|          | 0,362                 |
|          | 14,119                |
|          | 39                    |
|          | 550                   |
|          | 0,381                 |

### 3. Results and discussion

The data measured in and calculated from the tensile test show that the micro alloyed steel displayed values of yield strength higher by 4%, tensile strength by 2% and approximately the same values of ductility as the two-phase ferritic-martensitic DP 600 steel. However, the values of the material constant $K$ were 48% greater for the two-phase ferritic-matrix steel DP 600 and the values of strain hardening $n$ were 12% greater than in the micro alloyed steel H 220 PD with ferritic structure. From the values of mechanical properties the measurements of which are given in table 2, the deformation work $W_{\text{pl}}$ was calculated as the area under the curve of dependence of the actual stress on the actual deformation according to equations (2) and (3).

\[
W_{\text{pl}} = \int_{0}^{x_{\text{max}}} F \, dl \tag{2}
\]

\[
W_{\text{pl}} = V_0 \cdot K \cdot \left( \frac{\varphi_{\text{g}}^{n+1} - 0.002^{n+1}}{n+1} \right) \tag{3}
\]

\[
\varphi_{\text{g}} = \ln \left( 1 + \frac{A_g}{100} \right) \tag{4}
\]

Where $V_0$ is the volume of the specific part of the sample,

- $K_{0.05}$ - material constant,
- $n$ - exponent of strain hardening,
- $\varphi_{\text{g}}$ - true uniform deformation.

At the moment of collision, only a certain plastic deformation is permissible, during which the lives of the passengers in the cabin will not be endangered (by intrusion of fragments into the passenger cabin). In this case, the admissible tensile stress can be expressed as the ratio between the actual stress and the degree of safety $k$.

\[
\sigma_{\text{dov,T}} = \frac{k \cdot \varphi_g^n}{k} \tag{5}
\]

The values calculated for deformation work $W_{\text{pl}}$ and the actual strength $\sigma_{\text{dov,T}}$ are given in tab. 3. Based on the values of resistance to deformation or the intrusion of unwanted fragments into the vehicle cabin calculated according to equation (5), it follows that at about 20% deformation of reinforcement made of DP 600, it is possible to expect 41% greater resistance to intrusion of unwanted fragments into the passenger cabin and the absorption capacity greater by 49% compared to where micro alloyed steel reinforcement H 220 HD is used.

This assumption has been verified by a three-point bending test (stretch-bending test) with stretching of sheet metal. From the recorded dependence of bending force as a function of the path, it follows that during the impact, deformation force increases linearly as the function of the path until the moment when the loading force reaches its maximum value. If we start with the assumption that the elastic deformation work is negligible (line 1-2 - figure 7), then the dissipated energy, or the deformation work, can be expressed as follows [1]:
The stiffness constant $c_{pl}$ was determined through regression analysis as direction of the force dependence line on the path – figure 9 and figure 10. Deformation work was calculated as the area under the curve of dependence of the bending force on deformation path. From the calculated values of the stiffness constant and deformation work, it follows that for DP 600, 39% higher values of stiffness constant $c_{pl}$ and 24% higher values of deformation work were achieved compared to micro alloyed steel H220PD.

The impact mechanism in the three-point bending test was simulated in the PAM-STAMP program. A 3D model of the bending tool was created in Creo 2.0, based on a real physical model – figure 8, which was imported into the simulation software PAM-STAMP 2G. Entering the material model data according to Krupkowski.

The bending force values dependent on the path of the bender were obtained by means of the Curve Plotter command -> Export active curves points in the simulation software PAM-STAMP 2G - figure. 9 and figure 10. These were then exported to MS Excel. The values calculated for deformation work and stiffness constants are given in table 3.

The values given in table 3 point to a good match of the stiffness constant determined by numerical simulation and the one determined by the experiment. The difference in values was 5% and 3% for H220PD and DP600, respectively. The DP 600 material with a two-phase ferritic-martensitic structure shows 39% higher values of the stiffness constant compared to the H220PD material. This means that it puts more intense resistance during deformation and is able to absorb more impact energy than H220PD micro alloyed steel over the same deformation path. A similarly good match was recorded between the experimentally measured deformation work and that calculated from the data obtained in numerical simulation (the differences ranged from 3 to 4%).
**Figure 9.** Dependence of bending force on bender path - H220PG

**Figure 10** Dependence of bending force on bender path – DP 600
4. Conclusion

The purpose of this paper was to verify the results of numerical simulation on the basis of experimental results obtained by the three-point stretch-bending test. H220 PD and DP 600 were used for experimental research. The structure of the DP 600 base material had two (ferritic-martensitic) phases with ferrite accounting for 85% and martensite for 15% of the mass. On the other hand, the microstructure of the base material of micro alloyed steel H220 PD was formed by ferrite.

Samples of the H220 PD base material showed higher values of yield and tensile strength in the tensile test at comparable ductility values than samples from the DP 600 material. However, the recorded values of resistance to intrusion by undesired fragments into the passenger cabin and the overall absorbency were higher in the DP 600 than in the H 220PD material. We assume that in the case of steel DP 600, with martensite content of approx. 15% of the mass, a more intensive strengthening occurs during deformation due to the presence of martensite in the structure.

A comparison of deformation forces, stiffness constants, and deformation work values found in the three-point bending test and numerical simulation shows that a very good match between the results has been recorded. Differences in the characteristics under scrutiny varied from 2% to 5%.

The obtained results point to a considerable potential of numerical simulation in optimizing the choice of materials for deformation members of a car's body.

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