Crashworthiness Assessment of Auto-body Members Considering the Fabrication Histories

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Abstract. This paper is concerned with crashworthiness of auto-body members considering the effect of fabrication. Most auto-body members are fabricated with sheet metal forming process and welding process that induce fabrication histories such as the plastic work hardening, non-uniform thickness distribution and residual stress. Crash simulation is carried out for auto-body members with LS-DYNA3D in order to identify the fabrication effect on the crashworthiness. The analysis calculated crash mode, the reaction force and the energy absorption for crashworthiness assessment with the forming effect. The result shows that the crash analysis with considering the forming history leads to a different result from that without considering the forming effect. The analysis results demonstrate that the design of auto-body members should be carried out considering the forming history for accurate assessment of the crashworthiness..

INTRODUCTION

The crashworthiness of a car has to be evaluated with the load-carrying capacity and the crash mode at the initial stage of auto-body design. Auto-body members such as a front side member should be designed to efficiently absorb the kinetic energy during the car crash in order to secure occupants from the impact and penetration. The estimation of the energy absorption efficiency of auto-body members requires the accurate crash analysis for the load-carrying capacity and the crash mode. In order to accomplish reliable crash simulation, crashworthiness of auto-body members should be evaluated considering the effect of stamping and forming as well as the dynamic properties of materials. As most load-carrying members of an auto-body are fabricated from the sheet metal forming process, they could possess wrinkling and thinning induced from forming as well as non-uniform distributions of the effective plastic strain and the thickness strain according to the forming condition and their final shapes. Many crash analyses have been, however, carried out neglecting the forming effect induced by stamping and forming processes for estimation of the crashworthiness of an auto-body, providing erroneous results in the crash mode and the amount of crash. Recently, the crash analysis has been performed for auto-body members considering forming effect such as the strain hardening and the non-uniform thickness distribution [1-6]. These studies insisted that the crash analysis of auto-body structures should be carried out considering forming effects for the purpose of reliable assessment.

Dutton *et al.* evaluated the crashworthiness of the side-rail considering variations of thickness, plastic strain and residual stress obtained from the hydro-forming analysis [1, 2]. Lee *et al.* carried out the crash analyses of a sheet formed S-rail and a hydro-formed tube considering the effect of the mesh configuration as well as the thickness, the plastic strain and the residual stress [3]. Kim and Huh considered not only effects of the thickness variation and the effective plastic strain but also the effect of the final formed shape in the collapse analysis of an S-rail structure using the finite element limit analysis [4, 5]. Mikami *et* *al.* carried out the frontal crash analysis of a car considering the thickness variation and the plastic strain for the front side member and the under frame [6].

In this paper, the forming histories of a front side member are obtained from simulation of stamping and forming processes so that they can be considered in estimation of its crashworthiness. Since front side members should play an important role in absorption of the kinetic energy during the front crash, they are fabricated from sheet metals. Forming analysis of each panel of the front side member is carried out with an explicit elasto-plastic finite element analysis code, LS-DYNA3D. Non-uniform distributions of the effective plastic strain and the thickness strain in formed panels are obtained as the forming history from simulation of sheet metal forming. As the first step, draw-bead analysis is performed for calculation of the restraining force of draw-beads with an implicit elasto-plastic finite element analysis code, ABAQUS/Standard. Secondly, the calculated restraining force is applied to forming simulation of each panel as the equivalent restraining force on the flange region. The thickness strain of the inner panel, frame-frt-in, is compared with the thickness strain in a real product for verification of the analysis result. Crash analysis of the front side member is carried out imposing the forming analysis result on the initial condition. Numerical simulation is performed with LS-DYNA3D in order to evaluate the crashworthiness of the front side member. In order to consider the non-uniform distributions of the effective plastic strain and the thickness as the condition for crash analysis, the forming histories are mapped into the new finite element mesh system. The crash analysis results of the front side member considering the forming histories are compared with that without the forming effect. The forming effect on the crashworthiness is investigated for non-uniform distribution of the thickness and the effective plastic strain separately. The crash analysis results well demonstrate that these forming histories greatly change the crash mode, the load-carrying capacity and the energy absorption efficiency of the front side member. It is noted from the results that design of auto-body members needs to consider the forming effects for a proper and accurate evaluation of the crashworthiness of a car with fabricated members.

FORMING ANALYSIS OF THE FRONT SIDE MEMBER

One of the most important members in frontal crash is a front side member which absorbs most of impact energy in frontal crash of a car. The main frame of a front side member is composed of seven panels as shown in Figure 1 for the finite element mesh system. The forming histories are calculated with the direct forming analysis for four panels that have great influences on the behavior of the front crash. The die, the punch and the blank holder are modeled with finite element patches for forming simulation of each panel. Figure 2 explains the tooling system with the draw-bead for the forming analysis. For the sake of the computational efficiency, the restraining forces of draw-beads in the dies are calculated with an implicit elasto-plastic finite element code, ABAQUS/Standard. The forming analysis is then carried out for four panels, imposing the calculated restraining forces as boundary conditions of the equivalent draw-bead [7-11]. The forming analysis, which is made up of the binder wrap process and the punch forming process, is performed with explicit elasto-plastic finite element code, LS-DYNA3D. Calculated forming results are considered in the crash simulation as the initial condition.

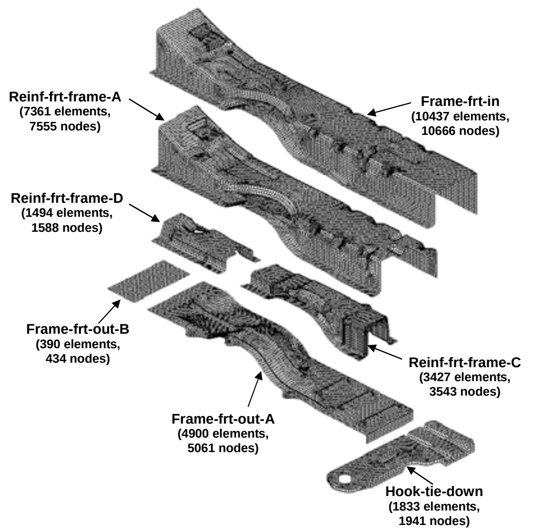


FIGURE 1. Finite element model of seven parts of a front side member.

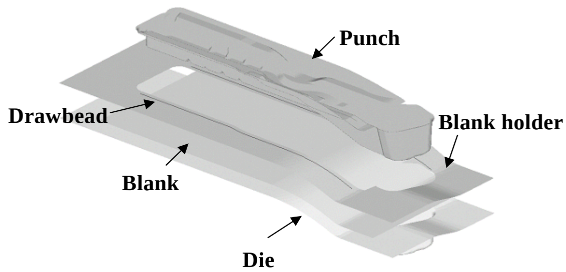
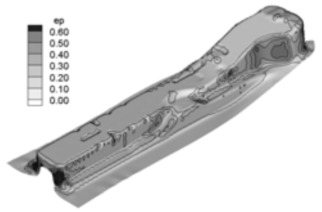
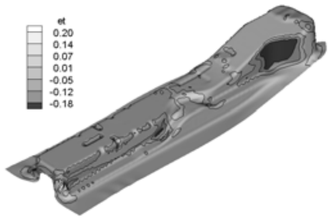


FIGURE 2. Initial setting of tools and the blank for the numerical analysis of the frame-frt-in in the front side member.



(a)



(b)

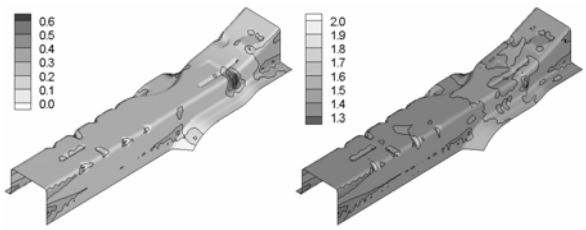
FIGURE 3. Final forming results of the frame-frt- in: (a) distribution of the effective plastic strain; (b) distribution of the thickness strain.

Figure 3 shows the effective plastic strain distribution and the thickness distribution in the frame-frt-in after forming simulation. The thickness distribution calculated has been compared with that in the real part for the frame-frt-in and the comparison showed close coincidence between the measured results and the calculated results[**]. The comparison fully demonstrates that the result from finite element forming simulation of the front frame member is highly reliable and its result of the effective plastic strain distribution and the thickness distribution can be applied to the crash analysis as the initial condition for better description of the real crash behavior.

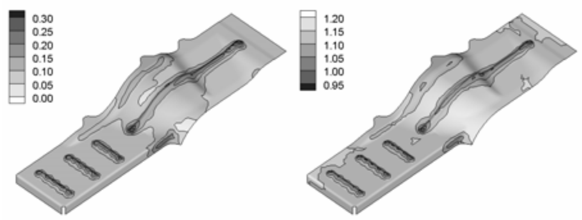
Forming analyses of other panels were also carried out with the same procedures in order to obtain the effective plastic strain distribution and the thickness distribution as the forming histories that are to be considered as forming effects in the crash simulation. Distributions of the effective plastic strain and the thickness were mapped into new finite element mesh systems for the crash simulation. Figure 4 shows the effective plastic strain distribution and the thickness distribution mapped from the simulation results for each part.

CRASH ANALYSIS OF THE FRONT SIDE MEMBER

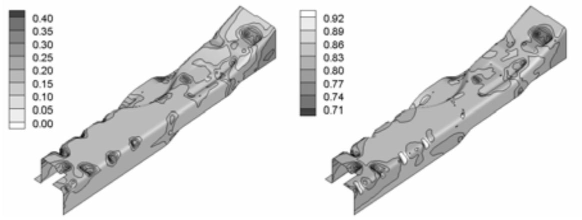
A finite element model of the assembled front side member for the crash analysis is shown in Figure 5. The total mesh system consists of 29842 four-node shell elements and 30788 nodal points. The welding points for assembling seven parts are 93 points that are also modeled in simulation. Finite element models of



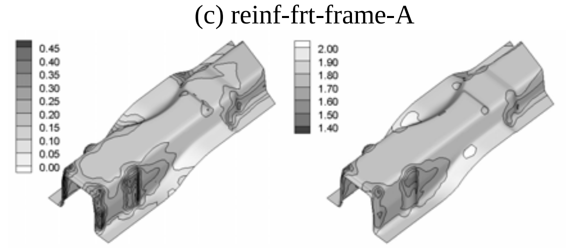
(a) frame-frt-in



(b) frame-frt-out-A



(c) reinf-frt-frame-A



(d) reinf-frt-frame-C

FIGURE 4. Distribution of the effective plastic strain and the thickness respectively in parts of the front side member:

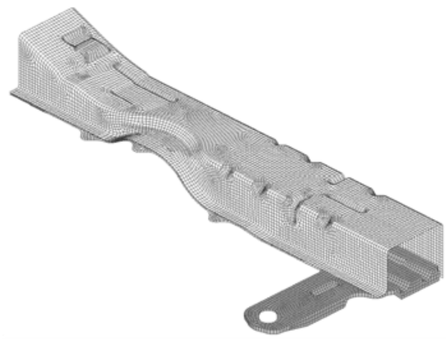


FIGURE 5. Finite element model of the front side member for crash analysis.

seven panels that compose the front side member were illustrated in Figure 1 with the number of nodes and elements specified for each panel. The panels are obtained from the formed ones by trimming. Forming histories obtained from the forming analysis in the previous section are utilized as the initial condition of

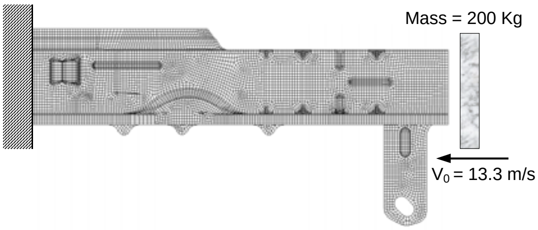


FIGURE 6. Schematic diagram for crash analysis of the front side member.

crashworthiness. Simulation conditions for the crash analysis of the front side member are explained in Figure 6. One end of the front side member is fixed and the other end is crashed by a moving rigid wall. The mass of the rigid wall is 200 kg and its initial velocity is 13.3 m/s. The crash analysis has been carried out for 30 milli-seconds.

The material specification and the thickness for seven panels of the front side member are shown in Table 1. Dynamic behavior of materials is described with the Johnson-Cook constitutive relation as shown in Equation (1) which has five material constants: A, B, n, C and m [12,13].

$$\bar{\sigma} = \left[A + B\bar{\varepsilon}^{n}\right]\left[1 + C\ln\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right]\left[1 - T^{*m}\right] \quad (1)$$

where

$$T^{*} = \frac{T - T_{room}}{T_{melt} - T_{room}}, \quad \dot{\bar{\varepsilon}}_0 = 1/\sec. \quad (2)$$

Table 1. Materials with the initial thickness for each part of the front side member.

Part	Material	Thickness (mm)
Frame_frt_in	SPRC40	1.6
Frame_frt _out_A	SPRC40	1.2
Frame_frt _out_B	SPRC40	1.2
Reinf_frt_frame_A	SAPH38	0.9
Reinf_frt_frame_C	SPRC45	2.0
Reinf_frt_frame_D	SPRC45	1.6
Hook_tie_down	SPRC45	2.0

The constants for materials of the front side member are obtained from the static and dynamic tensile test with Instron 5500, Instron 8032, and a High Speed Material Testing machine[*] as well as a tension split Hopkinson bar apparatus [13]. The experimental results are tabulated in Table 2.

Table 2. Material constants in the Johnson-Cook constitutive relation for the dynamic material properties.

Material constant	SAPH38	SPRC40	SPRC45
A (MPa)	295.5	294.1	345.1
B (MPa)	550.39	667.5	703.2
n	0.576	0.622	0.6
C	0.039	0.06	0.046
m	0.43	0.375	0.33

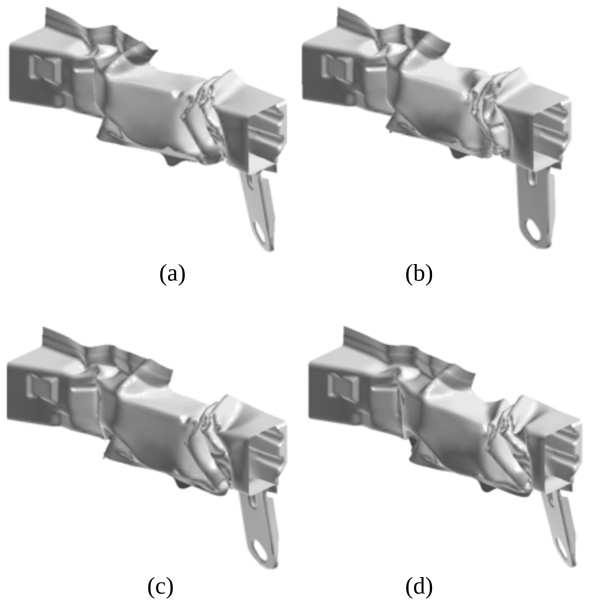


FIGURE 7. Deformed shapes of the front side member at 30 msec: (a) without forming histories; (b) with the thickness distribution; (c) with the effective plastic strain distribution; (d) with all forming histories**.**

The crash analysis has been carried out in the four different cases: one without considering fabrication effects; one with considering the thickness distribution only; one with considering the effective plastic strain distribution only; and one with considering all fabrication effects. Figure 7 shows deformed shapes of the front side member in four different cases of simulation. The deformation proceeds from the struck end since the end region has several grooves to induce axial folding. After the front region is crushed with folding, the deformation proceeds to the rear region absorbing more kinetic energy. The results show that the first and second ones deform more than the third and forth ones. The third one with considering the effective plastic strain distribution is the strongest while the second one with considering the thickness distribution is the weakest. It is because that the effective plastic strain distribution plays a role as

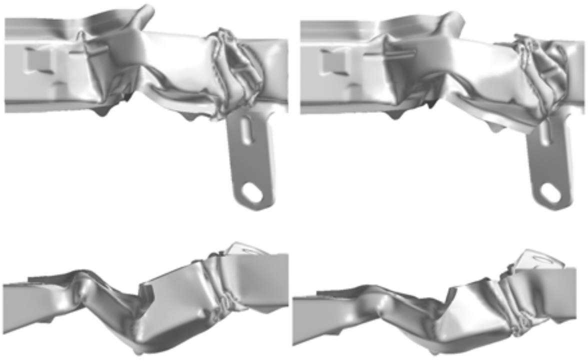


Figure 8. Comparison of deformed shapes of the front side member: (a) without forming histories; (b) with all forming histories

reinforcements in crash with the increased flow stress and the thickness distribution plays a role as defects in crash because of thinning due to stamping. When the effective plastic strain is considered as the forming history, the deformation proceeds less and slower than others. When the thickness is considered, deformation is concentrated on dimples in the grooved region and thus the energy is absorbed less than others.

Figure 8 demonstrates that the deformed shape with all forming histories considered is different from the one of the designed front side member that did not consider any forming effect. The region with dimples undergoes severer deformation when the forming effect is not considered than when the forming histories are considered. The middle region undergoes more remarkable bending when the forming effect is not considered than the one with all forming histories considered. It is because the bending in the middle region is delayed when the effective plastic strain distribution are considered as the forming histories. These results show that the deformation mode is greatly changed when forming histories are considered in the crash analysis. The most influencing factor is the non-uniform distributions of the effective plastic strain and the thickness. The comparison fully demonstrates that the forming histories have to be considered in the crash analysis for accurate assessment of the crashworthiness.

The reaction forces normal to the wall are plotted with respect to the crushing distance in Figure 9. The curves were obtained by filtering the original curves from the crash analysis with the SAE600 filter. The initial peak load is 138.3 kN when the forming effect is not considered and 155.6 kN when all forming histories is considered. The initial peak load increases by 13 % when only the effective plastic strain is consi-

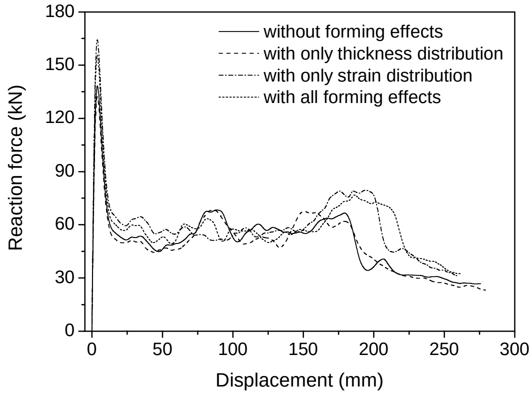


Figure 9. Reaction force during the crash of the front side member.

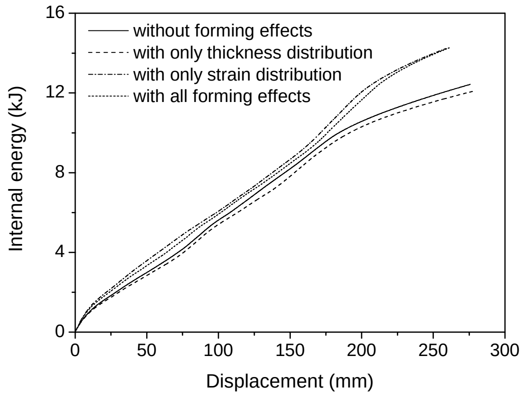


Figure 10. Comparison of the energy absorption with respect to the displacement in the front side member during the crash for 30 msec.

red and decreases slightly when only the non-uniform thickness is considered compared to the one without the forming effect. The reaction force tends to increase more with deformation in case of the analysis considering the effective plastic strain than without considering the effective plastic strain. The results explain that the strain hardening with the effective plastic strain from forming processes makes the maximum load increased and the non-uniform thickness distribution with the thinned region can be considered as the initial defect of the front side member.

The absorbed energy during deformation is plotted in Figure 10. The figure also demonstrates that energy absorption increases remarkably when the effective plastic strain is considered and decreases slightly when the non-uniform thickness distribution is considered. The energy absorption of the front side member has a larger value when all forming effects are considered than the one without forming effect. The difference is 5.3 % at the crushing distance of 100 mm, 10.2% when the crushing distance is 200 mm, and 17.3 %

when the crushing distance is 250 mm. The most important phenomenon is that the energy absorption rate increases with deformation when the effective plastic strain is considered in the analysis, while the energy absorption rate decreases with deformation when the effective plastic strain is not considered. It is because that the deformation is delayed with the stiffened body when the effective plastic strain is considered. The figure shows that the displacement after 30 msec is 275.8 mm when the forming effect is not considered and 262.1 mm when all forming histories is considered. These results demonstrate that the strain hardening resulted from forming processes is dominant in calculation of the reaction force and energy absorption. It is noted from the results that the crash analysis of the front side member has to be carried out considering the forming effect, especially the effective plastic strain, for accurate assessment of the crashworthiness.

CONCLUSION

Crash analysis of a front side member has been carried out in order to evaluate the crashworthiness accurately considering the forming history. The analysis investigated the difference of the crash mode, the reaction force and the energy absorption between the results with considering the forming history and without considering the forming effect. Forming analyses of parts of the front side member have been carried out to obtain the distribution of the thickness and the effective plastic strain as the forming history that were considered as the initial condition in the crash analysis. Forming analysis includes draw-bead formation and drawing analysis as the equivalent condition in the binder wrap process and the punch forming process. The crash analysis results considering the forming history were compared with that without the forming effect. The comparison explains that the effective plastic strain is dominant in calculation of the crash mode, the reaction force and the energy absorption due to the strain hardening. The analysis results fully demonstrated that the forming history should be considered for accurate assessment of the crashworthiness at the design stage of auto-body members.

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