A comparative study of the hexahedral elements in LS-DYNA for crashworthiness simulation

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Abstract

The mesh behaviour and convergence rate of six hexahedral element formulations in LS-DYNA were investigated by means of crashworthiness simulation. The element formulations are: constant stress solid element (ELFORM 1), fully integrated S/R (Selective Reduced) solid element (ELFORM 2), fully integrated S/R solid element with reduced transverse shear locking (ELFORM -1 and ELFORM -2), 20-noded serendipity element (ELFORM 23), and 27-noded fully integrated S/R quadratic solid element (ELFORM 24). FE-simulations of the axial crushing of aluminium profiles were set up with these element formulations. The convergence rate of each element formulation was investigated by varying the mesh resolution. For validating the simulation results, four extruded profiles with rectangular hollow cross-sections were experimentally tested under quasi-static axial crushing load. On that basis, the performance of each element formulation was investigated in terms of their convergence rate, accuracy, and computational cost to elaborate an approach for future tasks. Finally, various aspects which should be considered while using these element formulations for this class of problem are discussed.

1 Introduction

It was shown previously [1] that, solid element shows better accuracy compared to plane stress shell elements in the simulation of aluminum extrusions subjected to axial crushing. However, in [1], only one solid element formulation (ELFORM 2: fully integrated S/R solid element) was studied. In the current paper, six different solid element formulations are studied in the context of the simulation of aluminum profile subjected to axial crushing. These elements can be divided into three groups [2] as shown in Table 1.

Group 1		**Group 2**		**Group 3**	
Standard Hexahedral Elements		Improved Hexahedral Elements		Higher Order Hexahedral Elements	
ELFORM 1	ELFORM 2	ELFORM -1	ELFORM -2	ELFORM 23	ELFORM 24
Constant stress solid element	Fully integrated S/R solid element	Fully integrated S/R solid intended for elements with poor aspect ratio (efficient formulation)	Fully integrated S/R solid intended for elements with poor aspect ratio (accurate formulation)	20-node solid formulation	27-noded, fully integrated S/R quadratic solid element

Table 1: The hexahedral element formulations studied in this paper.

2 Experimental work

Four extruded profiles of aluminum alloy 6060 T6 were tested under quasi-static axial crushing load. The dimensions of the tested specimens are shown in Fig.1.

The axial crushing experiments of the aluminum profiles were performed in an ITC ServoPress 225 machine. The profiles were placed into the machine without any clamping or joining. The crushing velocity was 1 mm/sec and the crushing length was 200 mm. The force-displacement curves obtained from the axial crushing experiments are shown in Fig.2.

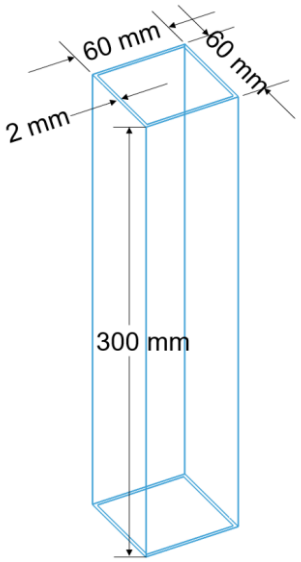

Fig.1: Geometry of the extruded profiles

Ideally, the force-displacement curves from the crushing experiments were supposed to be almost identical. Fig.2 shows that, the force-displacement curves are qualitatively comparable. However, the deviations in the curves from each other are still significant. These deviations could be the consequence of the geometrical and material imperfections in the profiles.

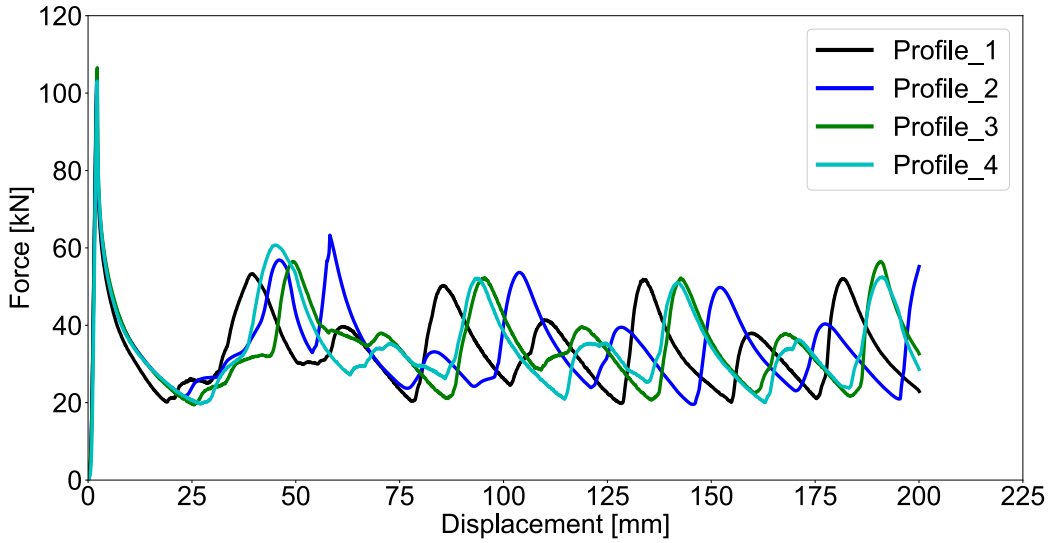

Fig.2: Force-displacement curve from the axial crushing experiments of the profiles.

According to our measurement, the wall thickness of the profiles varied at least in the range of 1.96 mm and 2.02 mm. Besides, even though the material is assumed to be homogeneous in the macroscale level, often there are local imperfections in the material. Since axial crushing of such a symmetric geometry is a bifurcation problem, even a minor imperfection can act as a natural trigger and have noteworthy influence.

The energy absorption and the peak force associated with each profile are presented in Table 2. The peak forces are directly obtained from the force-displacement curves (figure 2). The energy absorption values are obtained by integrating the force-displacement curves.

Table 2 shows that, the energy absorption values and the peak forces obtained from the crushing experiments do not vary significantly from profile to profile. This clearly shows that minor geometrical imperfections and the local material imperfections do not have a major influence in the global

response of the profiles. Nevertheless, we computed the mean energy absorption and the mean peak force to use as reference values for the validation of our FE-simulation results.

	Energy absorption [kJ]	Energy absorption (mean ± standard deviation) [kJ]	Peak force [kN]	Peak force (mean ± standard deviation) [kN]
Profile_1	6.740	6.868 ± 0.086	102.088	103.783 ± 1.929
Profile_2	6.895		103.417	
Profile_3	6.926		106.550	
Profile_4	6.909		103.077	

Table 2: Energy absorption and peak force from the axial crushing experiment of the profiles.

3 FE-modelling and simulation

The extruded aluminum profile was modeled as deformable body whereas, the floor and the traverse were modeled as rigid body. A material card was prepared based on the uniaxial tensile test data. The tensile test specimens were cut from the aluminum profiles and the tests were performed according to [3]. The von Mises plasticity-based material model ***MAT_PIECEWISE_LINEAR_PLASTICITY** was used to characterize the material. From the axial crushing experiments, it was observed that there is no fracture in the profiles. Hence, no material failure criterion in the material card was included. The floor and the impactor were modeled as rigid body using ***MAT_RIGID**.

Three contact definitions were used to model the interactions between the profile, the floor, and the traverse. The contact between the floor and the profile was modeled with ***CONTACT_AUTOMATIC_SURFACE_TO_SURFACE**. The contact between the traverse and the profile was also modeled with ***CONTACT_AUTOMATIC_SURFACE_TO_SURFACE**. The self-contact of the profile was modeled with ***CONTACT_AUTOMATIC_SINGLE_SURFACE**.

The floor was constrained in every direction and the motion of the traverse was defined by ***BOUNDARY_PRESCRIBED_MOTION_RIGID**.

The aluminum profile was modeled with each of the solid elements mentioned in Table 1. The mesh resolution was varied to study the convergence rate and the accuracy. The aspect ratio of the elements was always kept close to one.

3.1 ELFORM 1

The mesh resolution was varied from one element through the thickness up to five elements through the thickness. The energy absorption and the peak force from the simulations are plotted against the number of elements through the thickness in Fig.3.

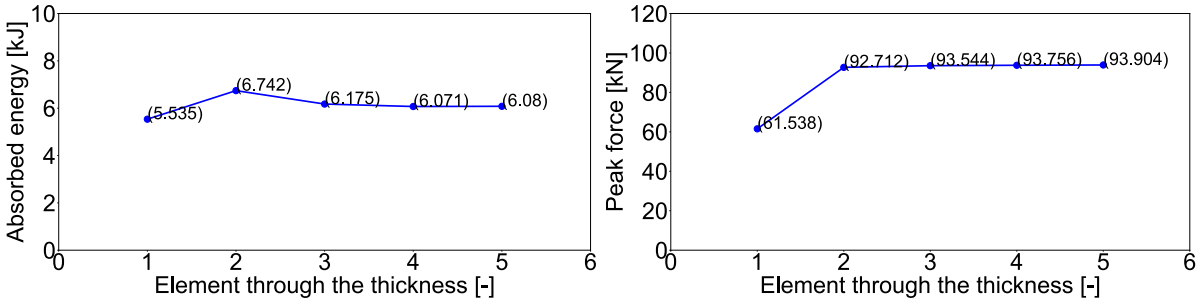

Fig.3: Convergence rate in terms of energy absorption (left), and peak force (right) for ELFORM 1.

As shown in Fig.3, convergence is already achieved for three elements through the thickness. However, ELFORM 1 is an under-integrated element and hence prone to hourglassing. Therefore, the hourglass energy needs to be checked for the reliability of the simulation results.

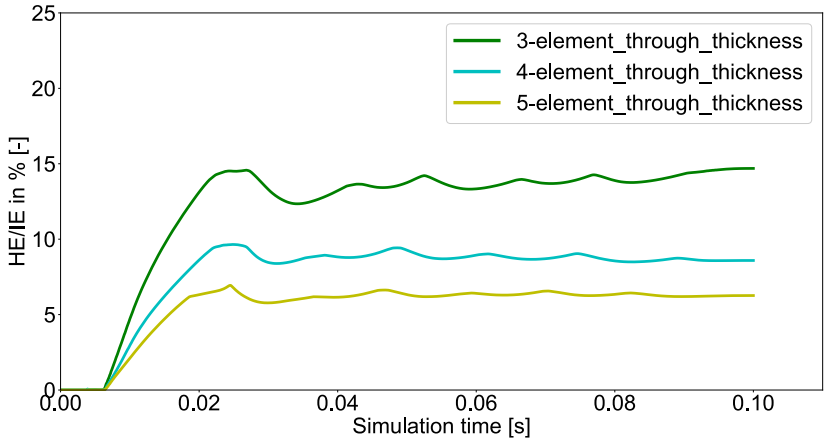

Fig.4: Ratio of hourglass energy to internal energy for ELFORM 1 during the simulation.

Ideally, the hourglass energy should be as little as possible compared to the internal energy. Based on our engineering judgement and experience, we chose an upper threshold value of 10%. According to this threshold value, the simulation results associated with three elements through the thickness is not reliable (Fig.4). Hence, four elements through the thickness is chosen as the converged mesh. The hourglass parameters used in the simulations are IHQ = 6, and QH = 0.1 in ***CONTROL_HOURGLASS**.

3.2 ELFORM 2

The mesh resolution was varied from one element through the thickness up to five elements through the thickness. The energy absorption and the peak force are plotted against the number of elements through the thickness in Fig.5.

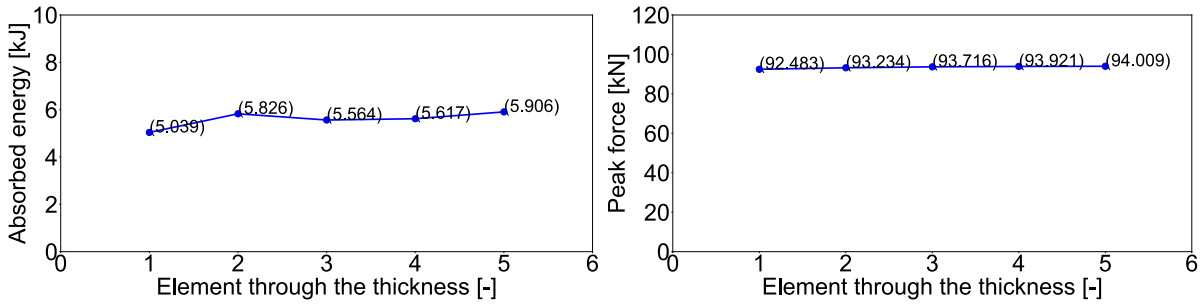

Fig.5: Convergence rate in terms of energy absorption (left), and peak force (right) for ELFORM 2.

As shown in Fig.5, convergence is already achieved for three elements through the thickness. However, the energy absorption values associated with five elements through the thickness slightly deviates. For further investigation, the internal energies associated with those three simulations are plotted in Fig.6.

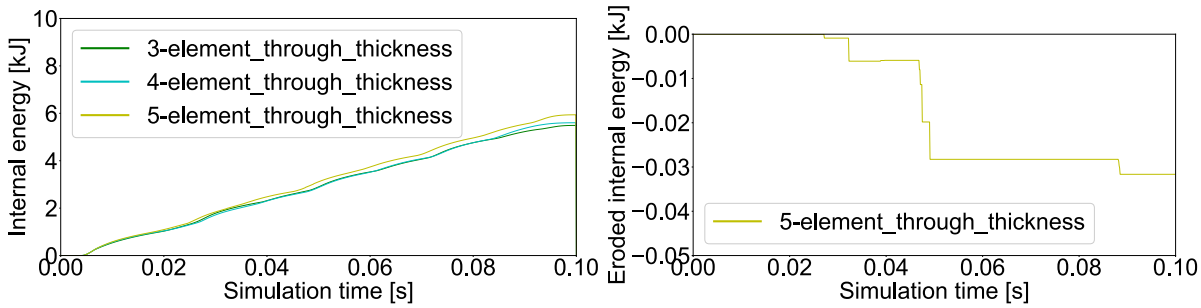

Fig.6: Internal energy (left) and eroded internal energy (right) for ELFORM 2.

Fig.6 shows that the internal energy associated with five elements through the thickness clearly deviates from the internal energies associated with three elements through the thickness and four elements through the thickness. The reason is the eroded internal energy resulting from the eroded elements (Fig.6).

Although there was no failure model in the material card, some elements were eroded since their timesteps dropped below the minimum timestep criterion. The minimum timestep criterion was defined by ERODE=1 in ***CONTROL_TIMESTEP** and DTMIN=0.1 in ***CONTROL_TERMINATION**. Such a criterion is necessary to prevent termination of any simulation due to negative volume of the elements. In the case of three elements through the thickness and four elements through the thickness, there was no eroded element and hence, no eroded internal energy.

The deviation in the energy absorption for five elements through the thickness (Fig.5) could be the consequence of the element erosion (Fig.6). Hence, it can be argued that the convergence is achieved for three elements through the thickness (Fig.5).

3.3 ELFORM -1

The mesh resolution was varied from one element through the thickness up to five elements through the thickness. The energy absorption and the peak force are plotted against the number of elements through the thickness in Fig.7.

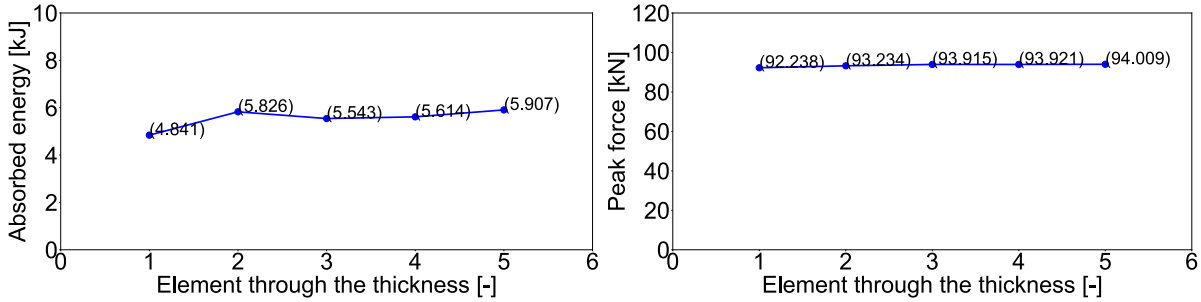

Fig.7: Convergence rate in terms of energy absorption (left), and peak force (right) for ELFORM -1.

According to Fig.7, convergence is achieved for three elements through the thickness. However, the energy absorption values associated with five elements through the thickness slightly deviates. For further investigation, the internal energies associated with those three simulations are plotted in Fig.8.

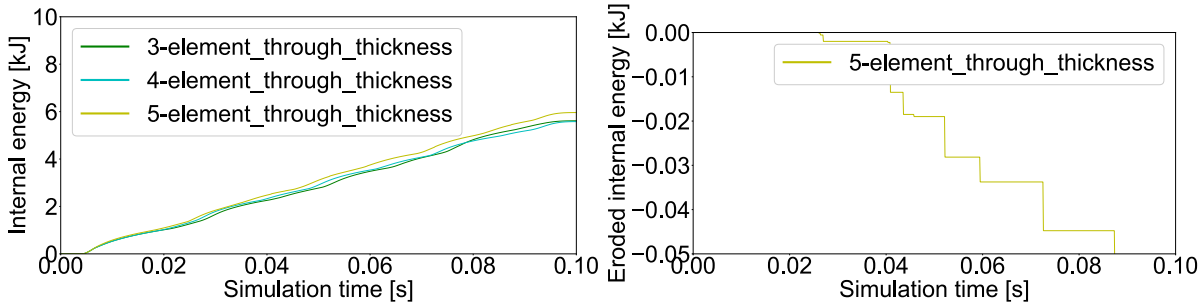

Fig.8: Internal energy (left) and eroded internal energy (right) for ELFORM -1.

Fig.8 shows that the internal energy associated with five elements through the thickness clearly deviates from the internal energies associated with three elements through the thickness and four elements through the thickness. The reason is the eroded internal energy resulting from the eroded elements (Fig.8) whereas, there was no eroded internal energy in the simulation models with three elements through the thickness and four elements through the thickness.

The deviation in the energy absorption for five elements through the thickness (Fig.7) could be the consequence of the element erosion (Fig.8). Hence, it can be argued that the convergence is achieved for three elements through the thickness (Fig.7).

3.4 ELFORM -2

The mesh resolution was varied from one element through the thickness up to five elements through the thickness. The energy absorption and the peak force are plotted against the number of elements through the thickness in Fig.8.

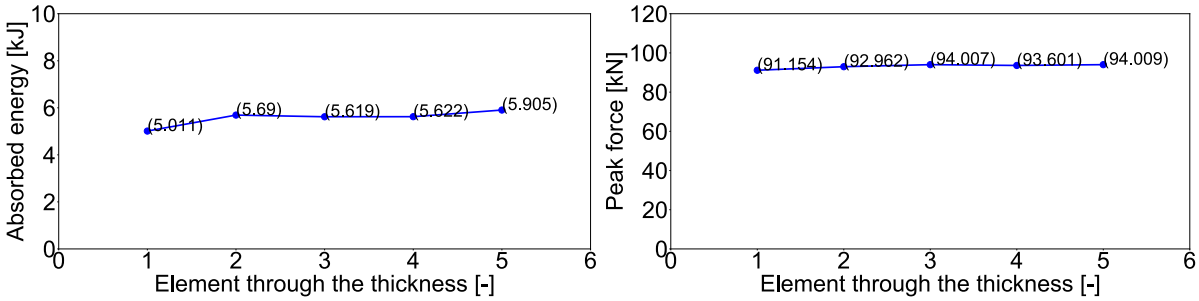

Fig.9: Convergence rate in terms of energy absorption (left), and peak force (right) for ELFORM -2.

Fig.9 shows that the convergence is achieved for three elements through the thickness. However, the energy absorption values associated with five elements through the thickness slightly deviates. For further investigation, the internal energies associated with those three simulations are plotted in Fig.10.

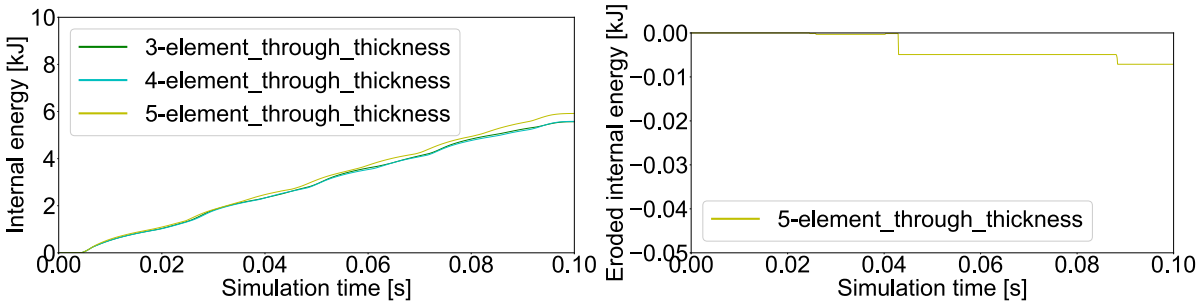

Fig.10: Internal energy (left) and eroded internal energy (right) for ELFORM -1.

Fig.10 shows that the internal energy associated with five elements through the thickness clearly deviates from the internal energies associated with three elements through the thickness and four elements through the thickness. The reason is the eroded internal energy resulting from the eroded elements (Fig.8) whereas, there was no eroded internal energy in the simulation models with three elements through the thickness and four elements through the thickness.

The deviation in the energy absorption for five elements through the thickness (Fig.9) could be the consequence of the element erosion (Fig.10). Hence, it can be argued that the convergence has already been achieved for three elements through the thickness (Fig.9).

3.5 ELFORM 23

This is a 20-node serendipity element (not fully quadratic). This element formulation is computationally very expensive compared to the eight node hexahedral elements. Hence, the mesh resolution was varied from one element through the thickness up to three elements through the thickness. The energy absorption and the peak force are plotted against the number of elements through the thickness in Fig.11.

Fig.11 shows that even three elements through the thickness is not sufficient for converged solution. However, a finer mesh resolution with this element formulation is not meaningful since the motivation behind such an element formulation is to achieve faster convergence. In addition, in the simulation model with one element through the thickness, significant amount of negative energy was observed which indicates penetration. This negative contact energy was prevented by setting TSSFAC = 0.45 in **`*CONTROL_TIMESTEP`**.

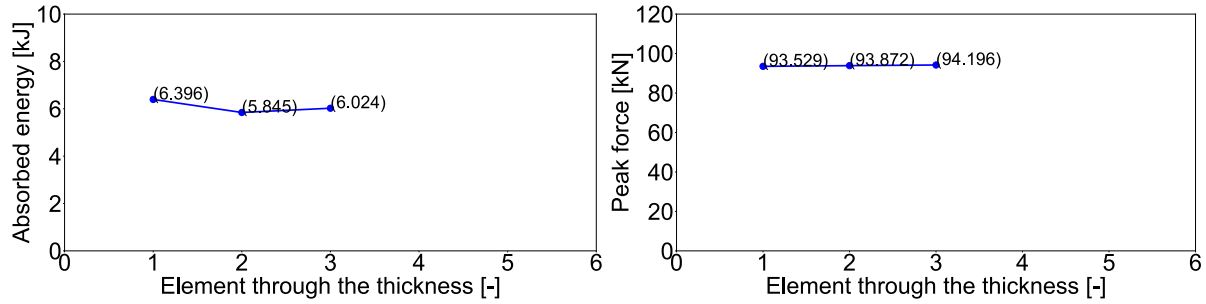

Fig.11: Convergence rate in terms of energy absorption (left), and peak force (right) for ELFORM 23.

3.6 ELFORM 24

This is computationally the most expensive element formulation among all the six element formulations mentioned in Table 1. However, the mesh resolution was varied from one element through the thickness up to two elements through the thickness. The energy absorption and the peak force are plotted against the number of elements through the thickness in Fig.12.

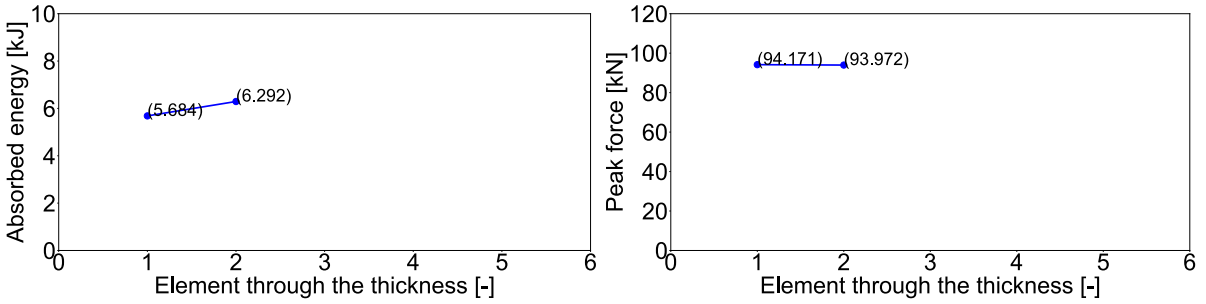

Fig.12: Convergence rate in terms of energy absorption (left), and peak force (right) for ELFORM 23.

Fig.12 shows that two elements through the thickness is not sufficient for converged solution. However, a finer mesh resolution with this element formulation is not meaningful since the motivation behind such an element formulation is to achieve faster convergence. In addition, in the simulation model with one element through the thickness, significant amount of negative energy was observed which indicates penetration. This negative contact energy was prevented by setting TSSFAC = 0.45 in **`*CONTROL_TIMESTEP`**. For two elements through the thickness, the SOFT parameter was set to 1 to prevent an error termination causing from negative volume of the elements.

3.7 FE-Simulation summary

Based on the simulation results and the discussions from sub-section 4.1 until sub-section 4.6, six simulations were chosen to study the performance of the element formulations.

ELFORM	No. of elements through the thickness	Remarks
1	4	Convergence achieved based on our engineering judgement
2	3	Convergence achieved based on our engineering judgement
-1	3	Convergence achieved based on our engineering judgement
-2	3	Convergence achieved based on our engineering judgement
23	3	Convergence not achieved. Further mesh refinement was not meaningful
24	2	Convergence not achieved. Further mesh refinement was not meaningful

Table 3: Simulations chosen to study the performance of the element formulations.

4 Results comparison and discussion

4.1 Accuracy

The force-displacement curves obtained from the simulations (Table 3) are compared with those from the experiments (Fig.13).

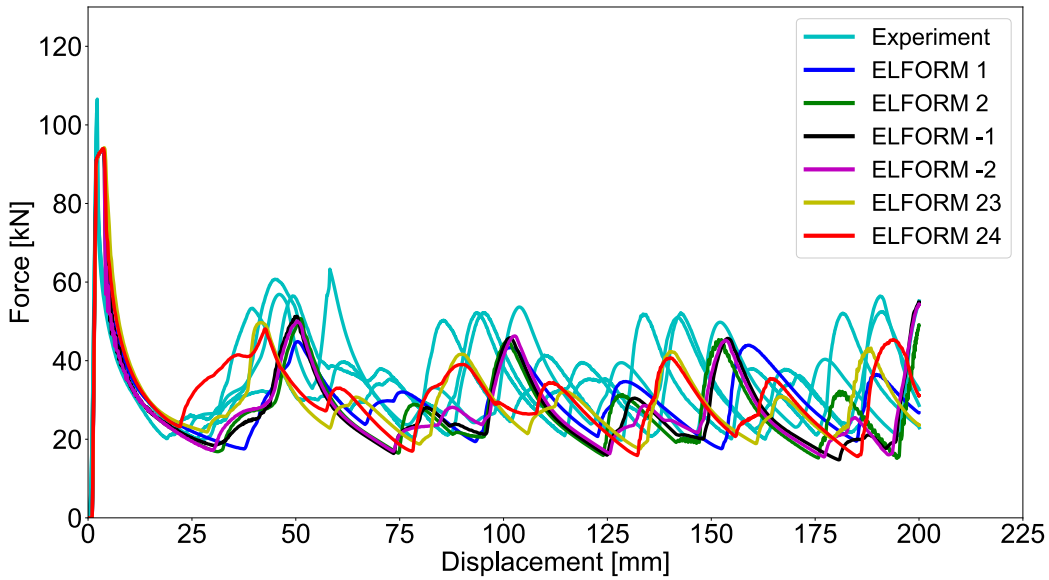

Fig.13: Force-displacement curves from the experiments and the simulations (table 3).

Fig.13 shows that the force-displacement curves from the experiments and those from the simulations are qualitatively comparable. However, for a better comparison (quantitative), the energy absorptions and the peak forces are presented in Table 4.

ELFORM	Energy absorption [kJ]	Energy absorption (Experiment) [kJ]	Deviation [%]	Peak force [kN]	Peak force (Experiment) [kN]	Deviation [%]
1	6.071	6.868 ± 0.086	11.60	93.756	103.783 ± 1.929	9.66
2	5.564		18.99	93.716		9.70
-1	5.543		19.29	93.915		9.51
-2	5.619		18.19	94.007		9.42
23	6.024		12.29	94.196		9.24
24	6.292		8.39	93.972		9.45

Table 4: Comparison of energy absorptions and peak forces between the simulations and the experiments.

Table 4 shows that the peak forces from the simulations are quantitatively comparable. However, they deviate from the experimental data by approximately 10%. This amount of deviation is acceptable since our material card was very simple. With a more sophisticated material card, this deviation can be reduced.

Different element formulations show different level of accuracy in terms of energy absorption. ELFORM 24 shows the most accurate performance with a deviation of 8.39% from the experimental value. However, to know whether this model achieved the mesh convergence, we need at least one more simulation with a finer mesh resolution. The same holds true for ELFORM 23 which shows even a higher deviation of 12.29%.

The accuracy of ELFORM 1 is also somewhat acceptable considering the simplicity of the material card. However, the influence of the hourglass parameters on the global energy absorption value still needs to be investigated.

ELFORM 2, ELFORM -1, and ELFORM -2 shows almost similar behavior in terms energy absorption. But they deviate from the experimental data by approximately 20%. A more sophisticated material card can reduce this deviation. However, still the accuracy might not be satisfactory. At this point, it should be noted that, the stress-strain data until the necking point obtained from the tensile tests was insufficient in terms of maximum strain. Hence, the flow curve was extrapolated by Voce hardening law and then calibrated by reverse engineering method. In the flow curve calibration process, FE-simulation of the tensile test was performed using ELFORM 1. Hence, it is necessary to investigate the influence of element formulation in the flow curve calibration by reverse engineering.

4.2 Computation time

All the simulations were performed in the same platform using 64 CPUs (Intel Xeon CPU E5-2667 v4 @ 3.20 GHz). The computation time of the simulations (Table 3) are normalized with respect to the computation time of ELFORM 1 (17 hours 50 minutes) and presented in Fig.14.

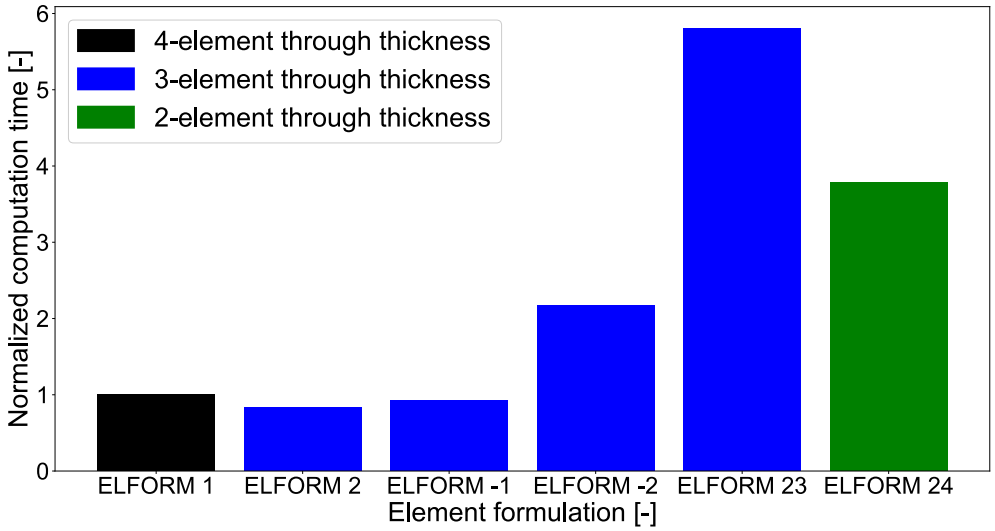

Fig.14: Comparison of computation time (normalized with respect to ELFORM 1) of the converged simulation models.

Fig.14 shows that ELFORM 1, ELFORM 2 and ELFORM -1 are relatively efficient and similar in terms of computational cost. Here it should be noted that, the element aspect ratio was always kept close to unity. However, such fine mesh resolution is only necessary in the thickness direction. Hence, the aspect ratio should be increased by increasing the element size in the longitudinal and in the transversal direction, and their performance should be studied. Thus, the computation time could be reduced significantly.

5 Summary

Six hexahedral element formulations were studied. Their performance was evaluated in terms of convergence rate, accuracy, computational time, and other modelling and simulation aspects. ELFORM 1 was found to be the most robust one. ELFORM 2, ELFORM -1, and ELFORM -2 were prone to negative volume when the mesh was refined. ELFORM 23 and ELFORM 24 showed severe robustness issues. In terms of accuracy, ELFORM 1 showed satisfactory performance. However, the effect of the hourglass parameters needs to be studied. ELFORM 2, ELFORM -1, and ELFORM -2 showed significant deviations from the experimental result. However, the influence of element formulation in the flow curve calibration by reverse engineering needs to be checked. Finally, further investigations can be done to evaluate the performance of these hexahedral elements when the element aspect ratio is not close to unity.

6 Acknowledgement

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7 Literature

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