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The effect of mass scaling and speed increase in explicit dynamic simulations using tensile test

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1. Introduction

A nuclear power plant is a highly responsible structure, where an accident can result in countless losses. The evaluation of the structural integrity of mechanical components prevents accidents from occurring. Mechanical testing is required to obtain the material properties, i.e., tensile test (quasi-static). In some cases, modeling these tests using the finite elements method (FEM) is interesting to get more information, i.e., the stress fields and absorbed energies. Sometimes, using damage models is necessary to simulate the specimen fracture process. One of the most used damage models is the Gurson-Tveergard-Needleman model (GTN) [1]. In Abaqus (2020), this model is available only in Abaqus/Explicit [2]. When the simulated speed is low (quasi-static), convergence problems can occur. These problems are due to a small-time increment required, and Abaqus (2020) cannot guarantee that the result is representative [2]. This problem can be solved using the mass scaling factor [2, 3] that increases the system mass or use a higher speed in the simulations. However, these methodologies may affect the results. Some authors have studied the mass scaling effects for several geometries [3, 4, 5]. This paper addresses the possibility of using a mass scaling factor or increases the speed to simulate a quasi-static tensile test. The study analyzed von Mises stress and kinetic energy to determine whether the results were not impacted by these methodologies.

2. Methodology

Three geometries based on tensile testing [6] were tested and simulated, changing the triaxiality with notches. Fig. 1(a) presents these geometries, the smooth (unnotched) specimen (S) with dimensions based on [6], and two notched specimens with different notches, 2 mm (N2) and 1 mm (N1). The methodology used in the tests follows the standards ASTM E8 [6]. A load vs. displacement curve is obtained from these tests and was used to calibrate the GTN damage parameters. The material used is an API X65 steel, applied mainly in pipelines. The properties needed in the simulations were obtained from the smooth geometry test. The properties were Young's modulus, Poisson's ratio, and density (Table I). The true stress vs. plastic strain curve, Fig. 1(d), was applied to model the plastic behavior. An axisymmetric model with symmetry in Y, Fig. 1(b), was utilized to decrease the computational cost. The mesh was created at Abaqus (2020), with a refinement close to the symmetry, and a minimum element size of 0.2 x 0.4 mm, Fig. 1(c). In the mass scaling simulations, a speed of 0.01333 mm/s in direction Y, Fig. 1(c), was used, and, for the other simulations, the speeds were 10, 25, 50, 75, and 100 mm/s. The calibration of the nine damage parameters (Table I) was made based on the literature information [7, 8].

For each geometry nine simulations were done (mass scaling factors: 10^6, 10^7, $5x10^7$, and 10^8, and speed: 10, 25, 50, 75, and 100 mm/s). The values 10^6 and 10 mm/s are the minima necessary for the convergence of the simulation. The parameters studied to verify the effect of increasing the mass or speed were the absorbed total deformation energy (internal energy), kinetic energy, and von Mises stress. The internal and kinetic energies were obtained for the whole model, while the stress for the centroid of the elements on the symmetry. Furthermore, the point in time used in these analyses was the point where the force is maximum.

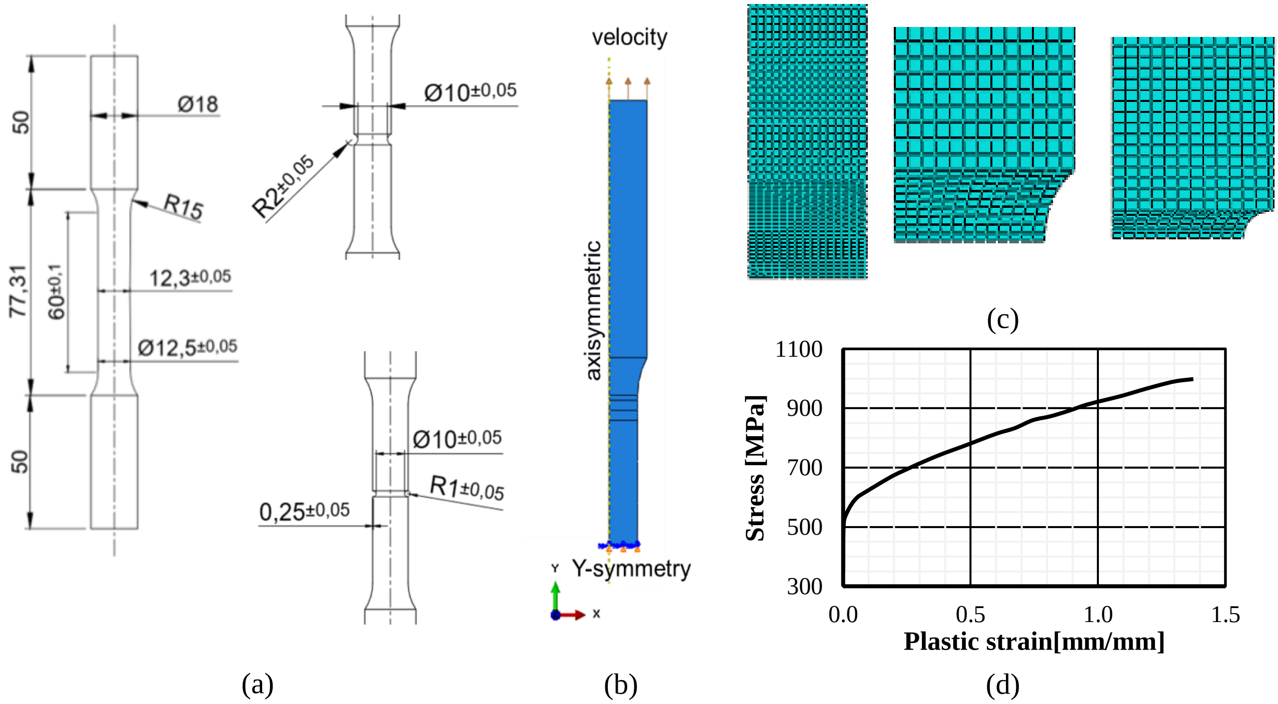

Figure 1: (a) tensile geometries; (b) load; (c) mesh; (d) plastic properties.

Table I: Material properties and GTN calibrated parameters

	***E* [GPa]**	***ν***	***ρ* [g/cm³]**	q_1	q_2	q_3	f_0	f_N	e_N	S_N	f_c	f_F
S				1.54	0.98	2.38	0.9997	0.0012	0.2	0.075	0.02	0.177
N2	190.521	0.3	7.85	1.54	0.98	2.38	0.9997	0.0010	0.3	0.050	0.02	0.177
N1				1.54	0.98	2.38	0.9997	0.0010	0.2	0.080	0.02	0.177

3. Results and Discussion

Table II presents the summary of some data from all simulations. The first observation was about the simulation time. Increasing the mass scaling factor (*f*) or the speed (*v*) decreases the simulation time (*T*). However, this decrease in time is not proportional, consequently, it is not interesting to increase further the value of *f* or *v*. Furthermore, the convergence for the notched specimens was better than for the smooth one. Simulations using $f = 10^6$ and $v = 10$ mm/s, to the smooth specimen, for example, were not completed due to convergence problems. In addition, the results of these simulations were not representative. The elements deformed excessively, and the failure did not start in the center of the specimen, as expected.

The second analysis utilized the internal (E_I) and kinetic (E_K) energies as parameters. The variation of the kinetic energy was expected since this energy depends directly on the mass and speed. In addition, the oscillations observed in the E_K curves by the simulation time are more expressive for high values of mass or speed. However, the maximum kinetic energy is significantly lower than the internal energy. Abaqus's manual recommends that the E_K be lower than 4% of the E_I [5]. This recommendation is valid for all the simulations.

As the strain rate effects were not considered, the stresses may not be affected by the increase in speed. The von Mises stress vs. X coordinate curve was plotted to compare the stress in symmetry. Figure 2 presents the curves for the standard specimen. These data were obtained for the selected point, and the displacements were obtained in the position where the strain gauge was placed in the specimen. Unfortunately, it was not possible to get the data for the same displacement for each simulation. This problem can explain the difference between the curves. In this case, the f = 10^6 and *v* = 10 mm/s curves were not considered, due to the convergence problems. It would be necessary to increase the number of points analyzed, which would increase the simulation time. Even then, it might not be possible to get the same displacement for all three geometries. The most significant difference between the two curves is around 2 MPa. The same happened to the notched specimens. Therefore, it is possible to use a factor of $5x10^7$ or a speed of 100 mm/s for all three geometries without affecting stress and energy.

Table II: Summary of the simulation

	N				**M2**				**M1**			
f	***T* [≈min]**	**E_I [J]**	**E_K [J]**	**PD [%]**	***T* [≈min]**	**E_I [J]**	**E_K [J]**	**PD [%]**	***T* [≈min]**	**E_I [J]**	**E_K [J]**	**PD [%]**
10^6	213*	651.9	0.00003	0.000004	109	275.2	0.00002	0.00001	115	253.3	0.00002	0.00001
10^7	157	751.4	0.00033	0.000044	50	283.4	0.00027	0.00010	33	256.2	0.00024	0.00009
$5x10^7$	38	773.1	0.00127	0.000165	22	283.3	0.00150	0.00053	17	256.7	0.00135	0.00053
10^8	25	777.0	0.00260	0.000334	14	283.2	0.00287	0.00101	13	257.0	0.00261	0.00102
***v* [mm/s]**	***T* [≈min]**	**E_I [J]**	**E_K [J]**	**PD [%]**	***T* [≈min]**	**E_I [J]**	**E_K [J]**	**PD [%]**	***T* [≈min]**	**E_I [J]**	**E_K [J]**	**PD [%]**
10	224*	594.7	0.00001	0.000002	126	271.6	0.00002	0.00001	133	250.3	0.00002	0.00001
25	118	744.8	0.00010	0.000013	65	282.1	0.00010	0.00004	56	255.0	0.00010	0.00004
50	65	749.6	0.00040	0.000054	35	283.0	0.00041	0.00015	33	256.8	0.00041	0.00016
75	41	768.8	0.00082	0.000107	23	283.1	0.00086	0.00030	22	256.7	0.00086	0.00034
100	34	773.7	0.00144	0.000186	16	283.4	0.00156	0.00055	15	256.7	0.00156	0.00061

Note: * convergence problems.

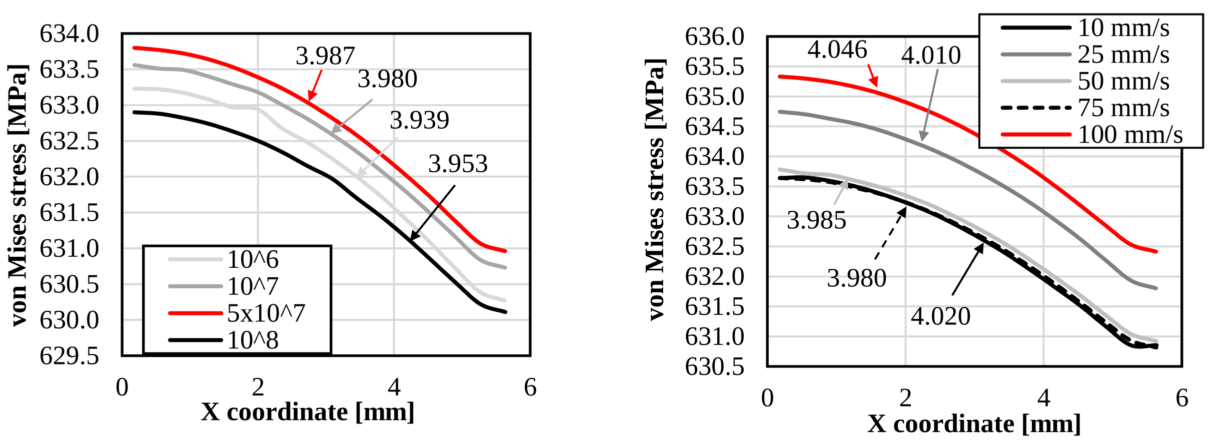

Figure 2: von Mises stress vs. X coordinate for the standard specimen

4. Conclusions

A representative numerical result, based on tensile tests and the GTN model, was achieved using a mass scaling factor or a higher speed. Tensile tests were conducted according to current standards to investigate the effect of these methodologies. The values that allow simulating for all three geometries are a mass scaling factor of $5x10^7$ or a 100 mm/s speed. Increasing these values further would not improve the results, and the decrease in simulation time is not significant. Kinetic energy is small, less than 0.0002% of the internal energy. Thus, if those values are applied, the energy results are unaffected. The comparison of the von Mises stress vs. the X-coordinate curves reveals a small difference between them. The most significant difference was around 2 MPa and can be explained by the different displacements considered for obtaining the data. Therefore, the experimental curve of a quasi-static tensile test was reproduced using both techniques without affecting the energy and the results of the von Mises stress. This study demonstrates the possibility of using a mass scaling factor or increasing speed to simulate a quasi-static tensile test.

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