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COMBINED BENDING AND PUNCHING DAMAGE OF REINFORCED CONCRETE SLABS UNDER IMPACT LOADING: PROJECTILE STUDIES FOR SCALED IMPACT TESTS

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ABSTRACT

In order to study the scale effect related to an impact loaded reinforced concrete wall, the size of the target wall is varied. A new projectile type needs to be designed and the scalability of the impact load shall be ensured. The impact force-time history and deformation of two different size of projectiles were analysed by using finite element method, Abaqus, and Riera's method. Crushing force in the Riera method, (Riera, 1968), was calculated using different folding mechanisms. All the considered methods predicted quite well and consistently impact force-time histories and final deformed shapes of impacted projectiles. Scalability of the considered projectiles was reasonably achieved considering the available projectile geometries and materials.

INTRODUCTION

Impact tests have been carried out since 2005 at VTT. Valuable information on nonlinear behavior of impact loaded reinforced concrete structures and related phenomena has been gathered. Experimental results have been utilized also in developing and validating numerical models and calculation tools. During the previous test campaigns, the span width of the target wall has always been 2 m. In order to study the scale effect, the size of the target wall needs to be varied. Due to practical reasons, such as unavailability of very small reinforcement bars, scaling down is not an option. Due to spatial limitations of the test hall, the increased span width of the target wall can be at maximum 3.5 m and the scaling factor thus becomes 1.75. The impact velocity in the upcoming geometrically scaled tests will be kept unchanged. In order to achieve comparable impact load for the larger scale test, the mass of the projectile should be increased by using the above mentioned scaling factor cubed. The mass of the reference scale projectile is 50 kg and the mass needed for the scaled projectile is 268 kg. A new projectile type needs to be designed and the scalability of the impact load shall be ensured. This is a challenging task since available selection of ferrite steel pipes and plates of different dimensions is rather limited. Numerical studies on impact tests carrier out with this type of projectiles on reinforced concrete targets are described in a parallel paper by Calonius et al. (2024).

PROJECTILE TESTS

The geometries of the projectiles are presented more detailed in a parallel paper by Fedoroff et al. (2024). The fuselage parts are made of ferritic steel pipes. The diameter of the reference projectile is 0.219 m and the wall thickness is 0.00635 m. The corresponding dimensions for the scaled projectile are d = 0.394 m and t = 0.011 m. The front cap parts are made by turning. The material of the projectiles is of type S355. The targeted masses of these projectiles, 50 kg for the reference projectile and 268 kg for the scaled projectile, were achieved by adjusting the thickness of the rear plate and adding some extra mass to the rear part of the projectile. The impact velocity of the projectile in the studied cases is 143 m/s.

CALCULATION METHODS

Analytical methods

In the Riera method, Riera (1968) the impact force F is calculated from

$$F = P_c + mv^2, \tag{1}$$

where P_c is the crushing force, m is the mass per unit length of projectile and v is the instantaneous velocity of projectile.

Alexander (1960) obtained an approximate solution for the crushing load for metal tube in axial loading by using an energy method. The model in Figure *1* consists of straight conical segments joined by plastic hinges. Also membrane energy is taken into consideration in the model. The material is assumed to be rigid perfectly plastic. Alexander considered outward and inward folding mechanisms and their average. In Wierzbicki (1992) the straight segment model was considered with an added eccentricity parameter $\tilde{m}$. Eccentricity parameter value $\tilde{m} = 0$ corresponds to completely inward folding. In the present case $\tilde{m}$ is set to 0.5.

In Wierzbicki (1992) was also developed a folding mechanism consisting of circular arcs. In Huang (2003) a straight segment was added to the mechanism of Wierzbicki. The model is shown in Figure 2. The model by Wierzbicki is obtained when $a = 1$ and the model by Alexander is approached when parameter a goes zero. However, due to finite wall thickness the hinge length parameter a must always be larger than zero. The use of curved folding models in impact analyses is considered e.g. in Saarenheimo (2012) and Saarenheimo (2015).

The model by Alexander was modified to simulate the actual curved folding in crushing tests in Jones (1989). To this end the effective crushing distance is defined, see Figure *2*,

$$\delta_e = 2h - 2x_m - t, \tag{2}$$

where the fold length h is shown in Figure 1, and t is the tube wall thickness.

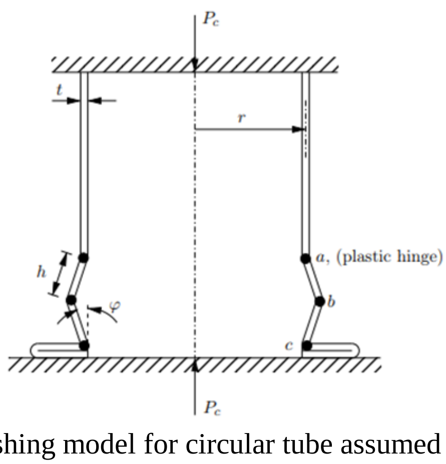


Figure 1. Crushing model for circular tube assumed by Alexander.

For a column of length $2h$, Jones (1989),

$$x_m \cong 0.28(h/2). \tag{3}$$

In Alexander's model during one fold, in the energy equation, the external work done by the axial force is $P_c 2h$. Assuming a more realistic curved folding, as shown in Figure 2, the external work becomes $P_c \delta_e$.

By minimising the axial crushing force in Alexander's model yields for fold the length

$$h_a = \sqrt{\pi r t/\sqrt{3}} \approx 1.347\sqrt{rt}. \quad (4)$$

Inserting x_m and h_a into the effective crushing distance equation yields

$$\delta_e/2h_a = 0.86 - 0.37(t/r)^{\frac{1}{2}}. \quad (5)$$

However, in Alexander's model the mean value of the circumferential strain variation is used. Using the actual value of ε_θ leads to an equation from which an approximate value for the plastic hinge distance becomes, Jones (1989),

$$h = 1.245\sqrt{rt}. \quad (6)$$

Inserting x_m and h into the effective crushing distance equation gives now an updated value for the ratio between δ_e and $2h$, the crushing distances in curved and flat foldings, denoted by c

$$c = \delta_e/2h = 0.86 - 0.40(t/r)^{1/2}. \quad (7)$$

The mean axial force using Equation (6) and assuming flat wrinkles becomes, Jones (1989),

$$P_{cf}/M_p = 29.4\sqrt{r/t} + 11.9 \quad (8)$$

where

$$M_p = \left(\frac{2}{\sqrt{3}}\right)\sigma_p t^2/4 \quad (9)$$

is the plastic yield moment of the tube wall per unit width, used also in Alexander's folding model.

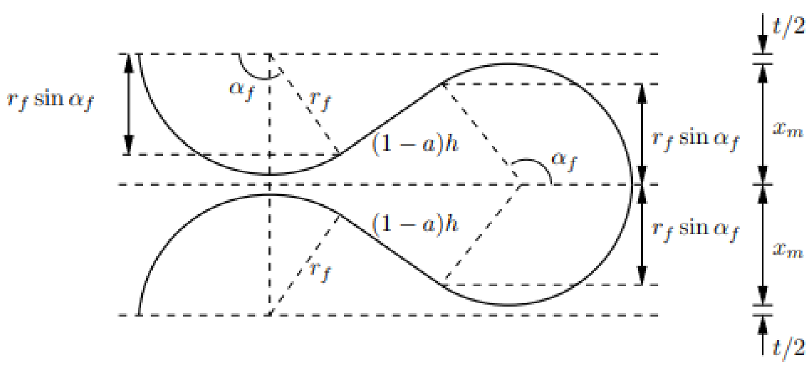


Figure 2. Folding model consisting of curved and straight parts. Deformation at the end of folding cycle.

Taking the actual curved buckled shape into account yields for the crushing force the formula Abramowicz (1984)

$$P_c = P_{cf}/c = M_p(29.4\sqrt{r/t} + 11.9)/(0.86 - 0.40\sqrt{r/t}), \quad (10)$$

where P_{cf} denotes the crushing force in flat wrinkling of Figure 1.

In dimensionless form the crushing force can be written in the form, Jones (1989),

$$\eta = P_c/A_c\sigma_y = 3.36(1 + 0.29\sqrt{\Phi})/(3.03/\sqrt{\Phi} - 1), \quad (11)$$

where σ_y is the static yield stress, A_c is the cross sectional area of the projectile, $\Phi = A_c/\Omega$, Ω is the area closed by the projectile cross section. For circular cylindrical shell $A_c = 2\pi rt$, $\Omega = \pi r^2$ and $\Phi = 2t/r$ where r is the tube radius and t is the wall thickness.

The used steel S355 in manufacturing the test projectiles is highly strain rate sensitive. According to the Cowper-Symonds formula, Jones (1989), the dynamic yield stress is

$$\sigma_{yd} = \sigma_y[1 + (\dot{\varepsilon}/D)^{1/q}], \quad (12)$$

where $\dot{\varepsilon}$ is the strain rate, q and D are material parameters.

In Alexander's crushing model only the circumferential membrane strain rate is considered for rate sensitive model, Jones (1989). During one flattening the average strain is $\varepsilon_\theta = h/2r$ and the time for one flat wrinkle to form is $t = 2h/v$, where v is the axial velocity of crushing. The average strain rate becomes

$$\dot{\varepsilon}_\theta = v/4r. \quad (13)$$

The viscoplastic (rate dependent) buckling force P_c^d is

$$P_c^d = P_c(1 + v/4rD)^{1/q}. \quad (14)$$

In order to take curved wrinkling into account v is divided by c in the above equation, Abramowicz (1984).

In the folding model consisting of curved and straight parts the hinge length is assumed to be $ah = bt$, where b is a parameter in the range from 2 to 4, Huang (2003).

In the impact force calculations, utilizing average crushing force, the number of occurred folds is

$$n_f = l_c/2h, \quad (15)$$

where l_c is the crushed distance and h is the distance of plastic hinges in Figure 1. The fold width (in the axial direction) is calculated from $w_f = 2x_m + t = 2h - \delta_e$.

Considering the variation of strains in both directions, thickness and axial, the strain rate sensitivity and strain hardening, the various terms in the energy equation, the bending and stretching energy rates, are calculated numerically by Gaussian integration on the shell middle surface and by Simpson integration in the shell thickness direction. Both parts, curved and straight, with lengths of $0.5ah$ and

$(1-a)h$ are divided into segments or elements as in the finite element method, into ten elements in the present analyses.

In the numerically integrated energy rate equation the strain hardening is taken into account by using the relationship $\sigma = E_p\varepsilon$, where E_p is the plastic modulus.

Finite element analyses

A commercial finite element (FE) code Abaqus/Explicit, Abaqus (2022), was used for numerical simulations. One quarter finite element model of the reference projectile contained over 19000 four noded shell elements with reduced integration. The number of finite elements used for the scaled projectile model was nearly 9000.

CALCULATION RESULTS COMPARED WITH EXPERIMENTAL FINDINGS

Numerical studies on impact tests with these two projectile sizes were carried out applying analytical methods and FE analysis. Various crushing load formulations applied in analytical methods are described above. The diameter to wall thickness ratio of the reference projectile D/t is about 33.5 and the corresponding ratio for the scaled projectile D/t is about 35 and the considered methods should apply for these cases. Simplifying the front can be modelled as flat. In the finite element analyses, of course, the actual front geometry can be modelled accurately. In the curved-straight folding model a spherical front cap, as used in making the previous projectiles in this impact project, can be taken into account using e.g. a rigid plastic spherical shell compression formulation of Gupta (1999). A yield stress of 355 MPa was assumed and rate sensitivity parameters were set to $D = 40.4\ 1/s$ and $q = 5$, so this steel type is highly strain rate sensitive.

Calculated impact load functions for the reference projectile with measured results are presented in Figure 3 and corresponding results for the scaled projectile are presented in Figure 4. Impact load is calculated by analytical methods with the average crushing force method, fvp, with the curved folding mechanism of Wierzbicki (1992), fvpc, and by assuming strain hardening with a modulus of 1000 MPa, fvpch.

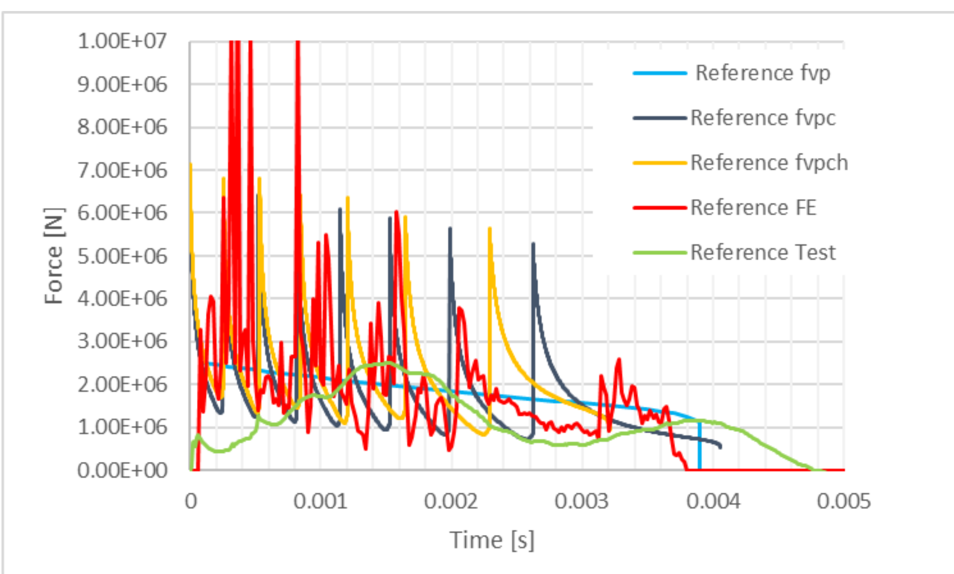


Figure 3. Force-time functions, reference test.

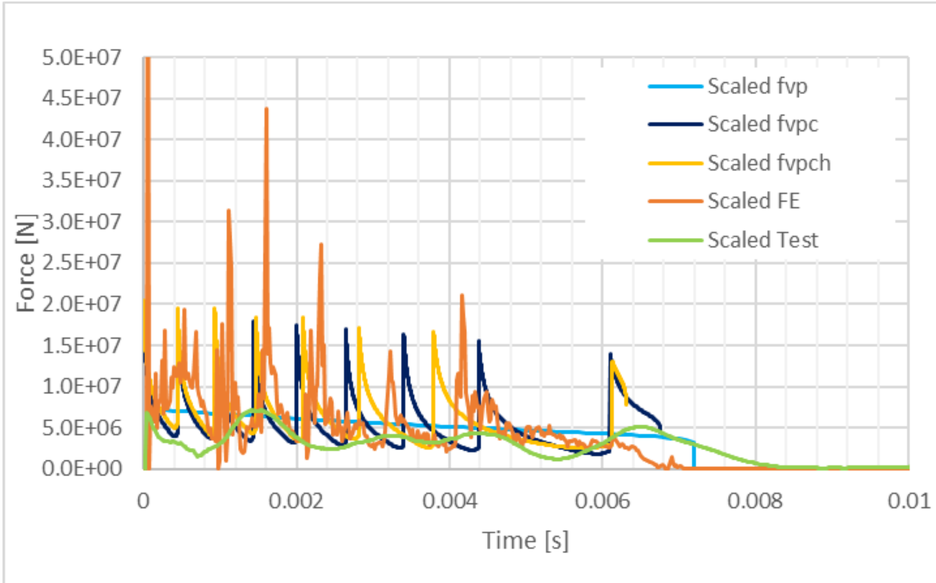


Figure 4. Force-time functions, scaled test.

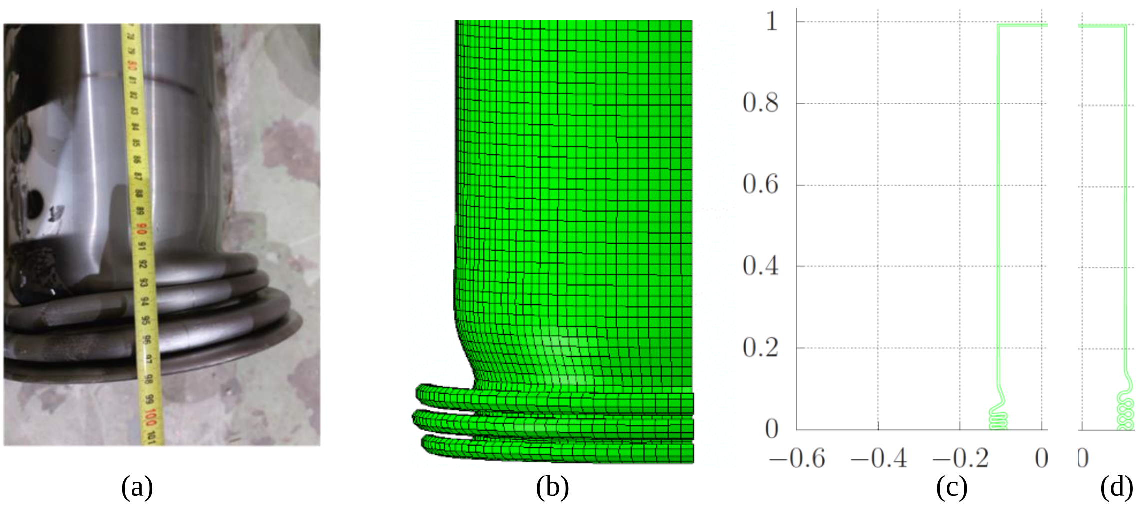
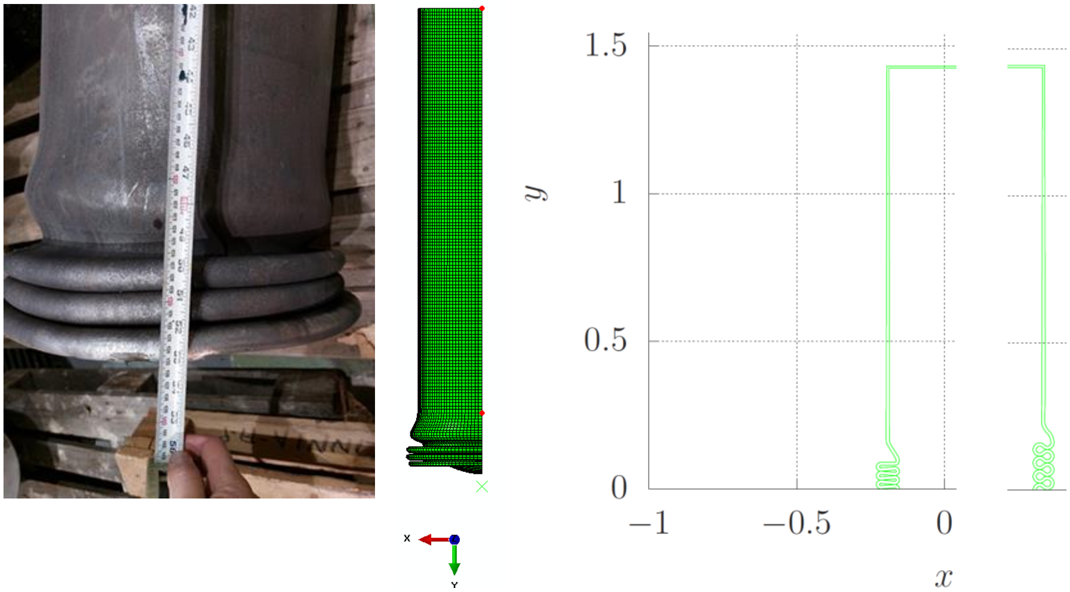


Figure 5. Deformed projectile, reference test.

The front part of the deformed reference projectile is shown on the left in Figure 5a. After the test, the length of the deformed projectile was 0.98 m and the length of the straight part was 0.92 m. The breadth of a fold (in the radial direction) is about 0.03 m. According to the finite element simulation, the number of folds after the impact test was three, see Figure 5b in the middle. The length of the deformed FE projectile model is 0.986 m and the length of the straight part according to the simulation is 0.91 m. Using the average crushing force of Equation (10) in Equation (1) the final length of the projectile becomes 0.95 m. The distance in Equation (6) $h = 0.037$ m, $\delta_e = 0.05$ m, the crushed distance is 0.27 m and the fold width is $w_f = 0.015$ m (in the axial direction). The length of final folded part becomes about 0.06 m and the number of folds is 4. Deformed shape of the projectile predicted by the curved-straight and curved folding models and assuming strain hardening material properties are shown in Figure 5c and Figure 5d, respectively. In the curved-straight folding mechanism calculation, the curved front part is modelled as a spherical cap with a height of 0.037 m. In the test, folds are more flattened than those predicted by the curved folding model of Wierzbicki (1992), (Figure 5d).



(a) (b) (c) (d)

Figure 6. Deformed projectile, scaled test.

The front part of the scaled projectile is shown on the left in Figure 6a. After the test, the length of the deformed projectile was 0.135 m and the length of the straight part was 0.120 m. The breadth of a fold was about 0.05 m. The length of the deformed FE model is 0.132 m and the length of the straight part is 1.22 m (Figure 6b, distance between the red dots). Using the average crushing force Equation (10) in Equation (1), the final length of the projectile is 1.36 m. The distance in Equation (6) $h = 0.057$ m, $\delta_e = 0.087$ m, the crushed distance is 0.51 m and the fold width is 0.027 m (in the axial direction). The final length of folded part becomes about 0.11 m and the number of folds is 4 in this case, too. Deformed shape of the projectile predicted by the curved-straight and curved folding models and assuming strain hardening material properties are shown in Figure 6c and Figure 6d, respectively. In curved-straight folding mechanism calculation, the front part is modelled as a spherical cap with the height of 0.066 m. In the test, folds are more flattened than those predicted by the curved folding model of Wierzbicki (1992), Figure 6d.

Scalability of the impact load by the scaled projectile is studied in Figure 7. The force-time histories obtained for the reference projectile impact are scaled by the scaling factor of 1.75. These curves are denoted by ‘Reference scaled’. Corresponding results of the considered scaled projectile are referred to as ‘Scaled’. The amplitudes and frequencies of impact force time histories calculated by finite element method and by analytical folding mechanism method are reasonably similar.

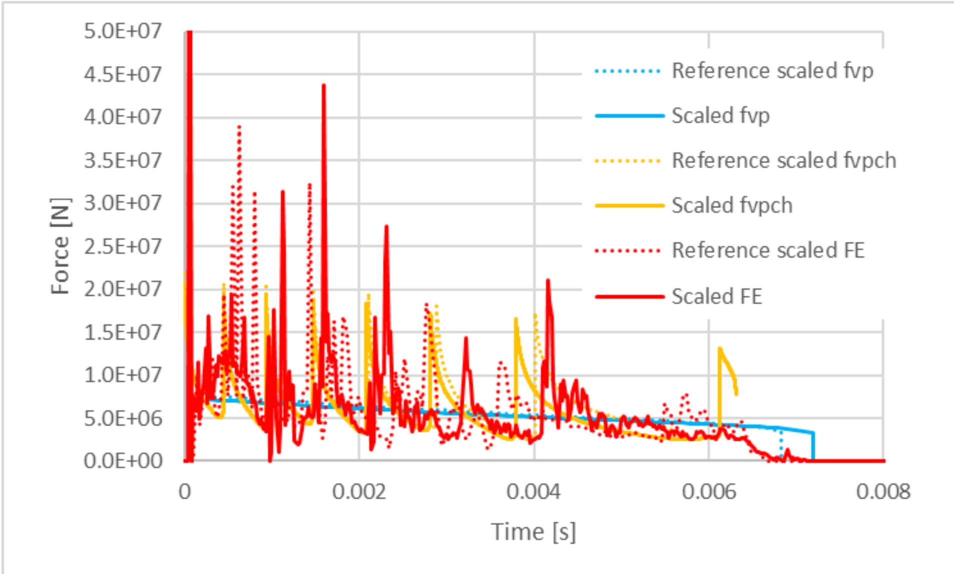


Figure 7. Comparison of force-time functions.

SUMMARY AND CONCLUSIONS

The impact force-time histories and deformations of two different sizes of projectiles were analysed by using finite element method, Abaqus, and Riera's method. Crushing force in the Riera method, Equation (1), was calculated using different folding mechanisms. For simplified quick analyses, the average crushing force equation of Jones, Equation (10), has been used. Also by this method the number of folds and the width and breadth of folds can be calculated, but not the force fluctuation during impact. In the average force crushing equation of Jones, the folding is assumed to be similar to the folding mechanism of Wierzbicki (1992) by which the formation of folds can be modelled leading to a fluctuating force history. In the latter method strain hardening as a function of strain and strain rate sensitivity of yield stress are taken into account at integration points along the mid surface and in the thickness direction of the tube, while in the average crushing force formulation rate sensitivity is included only in the radial stretching deformation and the same yield stress is used for the whole analysis. The eccentricity parameter $\tilde{m}$ was set 0.5 based on the present tests.

In tests, folds are more flattened than those predicted by the curved folding model of Wierzbicki (1992). By using the curved-straight folding mechanism of Huang (2003) better fit with the final deformed shapes of projectiles was achieved.

By finite element method, of course, all the mentioned features can be simulated without any additional assumptions using only geometrical and material data.

All the considered methods predicted quite well and consistently impact force-time histories and final deformed shapes of impacted projectiles, although the simplified crushing force formulations may perhaps not been originally meant to be applied in such rapid loading cases as the present ones. The amplitudes and frequencies of impact force time histories calculated by Abaqus and by folding mechanisms were reasonable similar. In the present cases the projectile is rather stiff and only few folds emerge. Calculations with a two degree of freedom model yielded quite similar displacement histories when using load histories determined by the average crushing force equation and by the corresponding curved folding mechanism resulting into force fluctuation.

Scalability of the considered projectiles was reasonably achieved considering the available projectile geometries and materials.

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