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Numerical evaluation of friction effects on the energy absorption of square profiles under bending load

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Abstract. Friction is often associated with undesirable effects on mechanical systems. However, friction could be useful to increase the energy absorption capacity of thin-walled structures subjected to bending loads. The current article proposes the use of friction as an additional energy dissipating mechanism to plastic deformation. For this purpose, three different friction fixtures are presented and numerically evaluated using Abaqus/Explicit software. The friction fixtures were placed at the ends of square profiles generating internal, external and combined friction. In all cases, the square profiles were made of aluminium 6063-T5. The reliability of the numerical results was experimentally validated by a modified three-point bending test with friction. The numerical results for the three arrangements were compared with the results obtained for a profile without friction. According to our results, in all cases friction improves the energy absorption performance of the square profiles in a range from 48.71% to 179.19%. Finally, the best crashworthiness performance was obtained when external friction is generated at the ends of the tube. An increase in the crush force efficiency (CFE) parameter up to 71.47% respect to a typical profile was computed. Thus, the effectiveness of the friction mechanism was demonstrated.

1. Introduction

Among the passive dissipating systems, the use of plastic deformation of thin walled-structures in car collisions is increasing [1]. For the specific case of lateral car collisions, automobile structural elements such as door-impact beams and pillars should be designed to experience bending loads [2, 3]. In order to understand the bending and energy absorption behaviour of thin-walled structures, several studies have been carried out [4, 5]. Many parameters affect the crashworthiness performance of these structures. However, the cross-section [6] material [7, 8,] and span [9] are among the most relevant. In all cases, the authors have focused their efforts on optimising the energy absorption of structures by plastic deformation [10]. Moreover, the incorporation of additional passive energy systems to plastic deformation also begins to be studied. In this way, viscoelastic and friction mechanisms are used [11, 12, 13]. The energy absorption by the viscoelastic mechanism is obtained when foams are used to fill the thin-walled structures. As a result, an increase in bending resistance is obtained by a change of the structural stiffness [14, 15]. In this context, the bending crashworthiness performance of empty and foam-filled circular profiles was analysed [16]. The study was conducted by quasi-static and dynamic three-point bending tests. Three different arrangements were evaluated including single and double tubes. It was concluded that the best crashworthiness performance and bending resistance is obtained when a double tube is filled with aluminium foam. On the other hand, optimisation procedures have been proposed, in this way, Jiang [17] carried out a multi-objective optimisation for a foam-filled double cylindrical tube design. The analysed structure was formed by two concentric cylindrical tubes with structural epoxy foam acting as filler between the tubes. Parameters such as diameter and thickness for the inner and outer tubes and density of the foams were explored. Relative to the original design, the optimised structure allowed an increase in specific energy absorption up to 57.17% and a decrease in peak load of 25.75%. Li [11] conducted an experimental investigation of the bending resistance and the energy absorption effectiveness of empty and foam-filled square and circular tubes. According to their experimental observations, the use of aluminium foam allowed and improvement in energy absorption capacity with a high resistance to bending deformation for double tubes. However, the best energy absorption capacity of 295.10 J was obtained by the foam-filled double square arrangement. Regarding the friction mechanism, this has been reported only for thin-walled structures subjected to axial compression. In this sense, the authors of [12] proposed an arrangement of two concentric tubes. When the compression load occurs, a rigid steel ring is press-fitted on top of a circular aluminium tube. Then, an expansion of the ductile structure is carried out. During this process, energy absorption by friction is obtained. Once the stroke of the steel tube has been reached, both tubes are plastically deformed. Lastly, it was reported that additional energy absorption mechanisms are plausible to improve the crashworthiness capacity of thin-walled structures. However, for the specific case of friction, this is mostly associated with axial compression and barely to structures subjected to bending load. Thus, the current article studies the effect of friction mechanism on the bending crashworthiness performance of square profiles. In this way, three friction fixtures are proposed and numerically evaluated using Abaqus/Explicit software. The friction fixtures were placed at the end of the square tubes. Finally, the assessment of the arrangements is carried out by a modified three-point bending test.

1.1. Dimensional and dimensionless crashworthiness parameters

The assessment of the profiles was carried out by calculating the energy absorption (E_a), mean force (P_m), peak load (P_{max}), specific energy absorption (SEA) and crush force efficiency (CFE) [18]. The mathematical expressions for each case are described in equations (1-4), where F is force, δ displacement and m mass.

$$E_a = \frac{1}{2}\sum_{i}^{n-1}(F(\delta)_{i+1} + F(\delta)_i)\cdot(\delta_{i+1} - \delta_i) \tag{1}$$

$$P_m = \frac{E_a}{\delta} \tag{2}$$

$$SEA = \frac{E_a}{m} \tag{3}$$

$$CFE = \frac{P_m}{P_{max}} \tag{4}$$

2. Modified three-point bending test with friction

Despite the efficiency of Abaqus/explicit to model the plastic deformation of thin-walled structures, the addition of friction effects needs to be validated. Thus, a first discrete model was developed and compared to experimental results. The model consists of a square tube with friction pads evaluated by a modified three-point bending test. The friction pads were placed at the bottom and top faces of both ends of the profile with a length of 50 mm. In order to avoid slipping effects and plastic deformation before the test, a pressure of 1 Nm was applied to the pads. The square profile was modelled with S4R elements and conferred with the elastoplastic properties for Al 6063-T5 described in table 1. Meanwhile, the friction pads were model with mechanical properties for steel using C3D8R elements. A Young modulus equal to 200 GPa, Poisson coefficient of 0.3 and density 7850 kg/m^3 were used. Lastly, from a mesh sensitivity analysis, a general element size of 3 mm was applied. Details of the discrete model are shown in figure 1.

Table. 1. Input material parameters for Al 6063-T5, [19].

Elasticity	Young modulus [MPa]	Poisson coefficient	Density [kg/m^3]
	66940	0.33	2700
Plasticity	Yield stress S_y [MPa]		
	158.79		

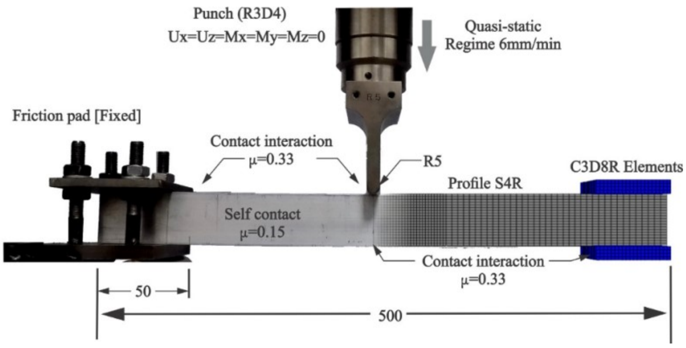


Figure 1. Modified three-point bending test for a square profile with friction pads, units in mm.

The bending force versus displacement curves is presented in figure 2a. Both curves are characterised by an initial increase in bending force (P_{max}) up to ~6 kN. As the ends of the profile are forced to slip, friction forces and bending deformation are observed. Friction forces contributed to keeping the P_{max} almost constant until a 15 mm of displacement is reached. Subsequently, a smooth decrease inin the force is observed. The area under both curves, which indicates the energy absorption, is similar for both models with a value close to 250 J. Respect to the theoretical bending deformation mode for a square structure described by Estrada et al. [6], the evaluated arrangement presents the same pattern at the mid-section. However, an additional deformation is present at the ends of the profile as illustrated in Figure 2b. Besides minor differences in E_a and P_{max} of less than 5% the numerical results correctly predict the plastic deformation behaviour of the structure. Thus, we continue with our numerical study of friction fixtures to improve the energy absorption capacity of square profiles.

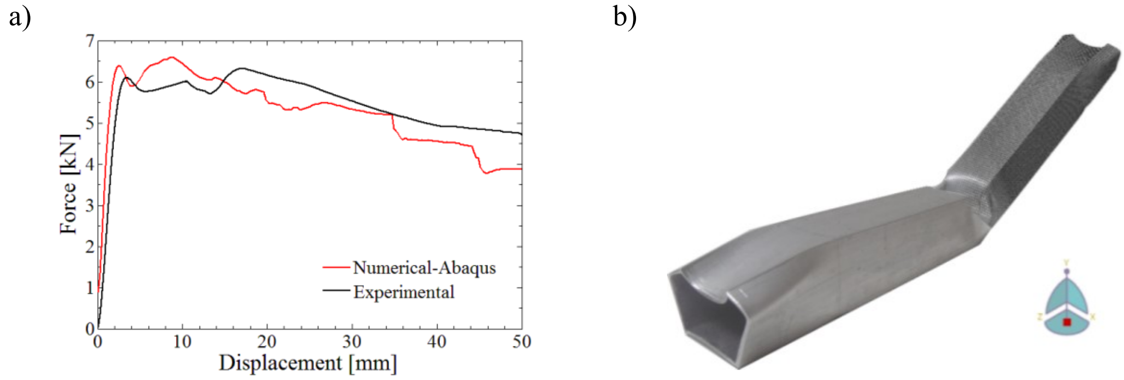
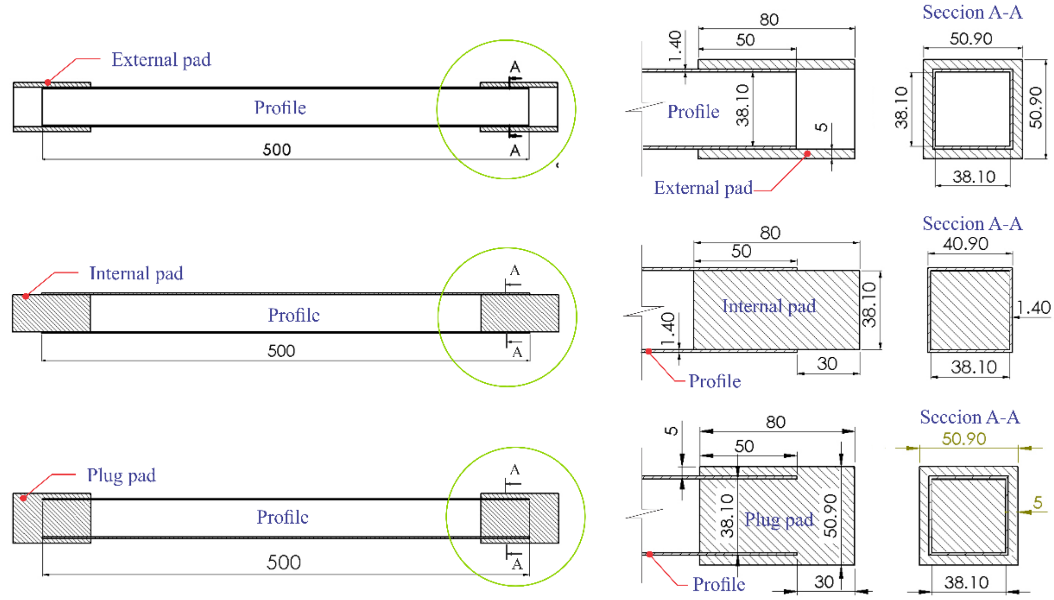


Figure 2. a) Force-displacement curve and b) final deformation state of a square profile under a modified three-point bending test.

3. Numerical simulations

The main objective of this article is to analyse friction effects on the bending and crashworthiness capacity of square tubes. For this purpose, three different friction fixtures inspired in [20] were designed and evaluated by a modified three-point bending test. The friction fixtures were placed at the ends of the square profile. The dimensions of the tube's cross-section are 40.9 x 40.9 mm, length equal to 500 mm and thickness of 1.40 mm. In order to evaluate just the friction and avoid a pre-stress state at the ends, a perfect assembly was considered. The friction mechanisms are designed to generate internal, external and combined friction. For comparison, a typical square profile without friction was also evaluated. Details of the studied arrangements are presented in table 2.

Table 2. Numerical setup, units in mm.



Arrangement code	Cross-section	Thickness of the tube [mm]	Mass of the Tube [kg]	Generated friction	Total contact area [mm²]
S-00		-	-	-	-
S-IF		1.437	43.815	Internal	7620
S-EF		1.442	41.910	External	7620
S-CF		1.445	40.005	Combined	15240

4. Results

The assessment of the arrangements with and without friction was carried out by the study of the bending force v displacement curves. As illustrated in Figure 3, at the beginning of the bending process all structures presented an increase in force close to 7 kN. Once this value is reached two behaviours were observed. The first group is formed by the typical square profile (S-00) and the arrangement with external friction (S-EF). In both cases, after reaching the maximum peak load (P_{max}), a stabilisation process of the force was observed. The opposite case was observed for the second group (S-IF and S-CF) where, contrary to what was expected, a continuous increase in the bending force is achieved. The explanation for this behaviour is associated with the pads acting as a restraining force on both ends. Thus, as the bending test is carried out, friction forces and plastic deformations at the ends are generated. Meanwhile, the S-00 profile presented only bending and crushing deformation at its mid-section.

The mechanical response of the structures is complemented by calculating the energy absorption which is presented in figure 4. Although all the square profiles present the same mass (0.290 kg), the use of a frictional pad increased the energy absorption capacity of the arrangements in all cases. However, the best E_a capacity is obtained when internal and external frictional forces are generated on arrangement S-CF.

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The amount of energy absorbed by the structure is determined by its plastic deformation and the frictional forces. Friction of the fixture at the ends of the profile modifies the bending deformation of a typical square profile without friction. As seen in figures 5-6 the frictional pads induce additional plastic deformation at the ends. Hence, as the frictional contact area increases, higher resistance to bending deformation beneath the punch is observed. Thus, minor plastic deformation is observed at the ends.

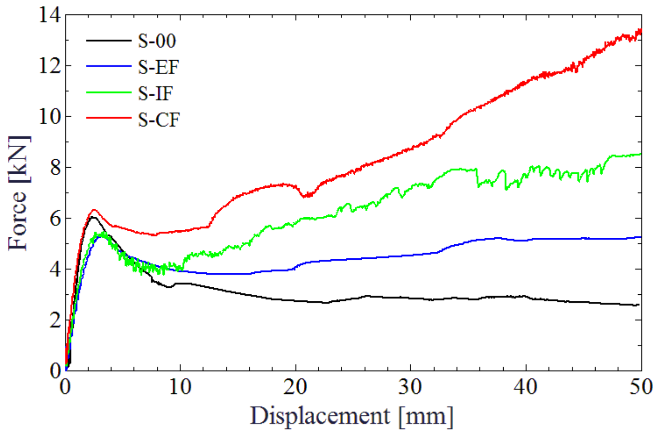

Figure 3. Comparison of force vs. displacement curves for the evaluated structures.

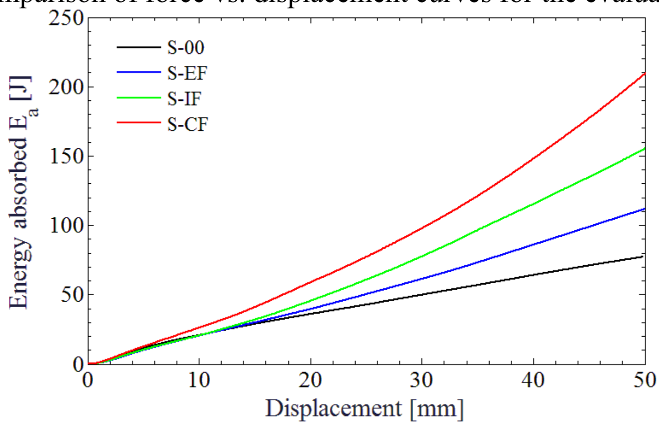

Figure 4. Energy absorption for evaluated structures.

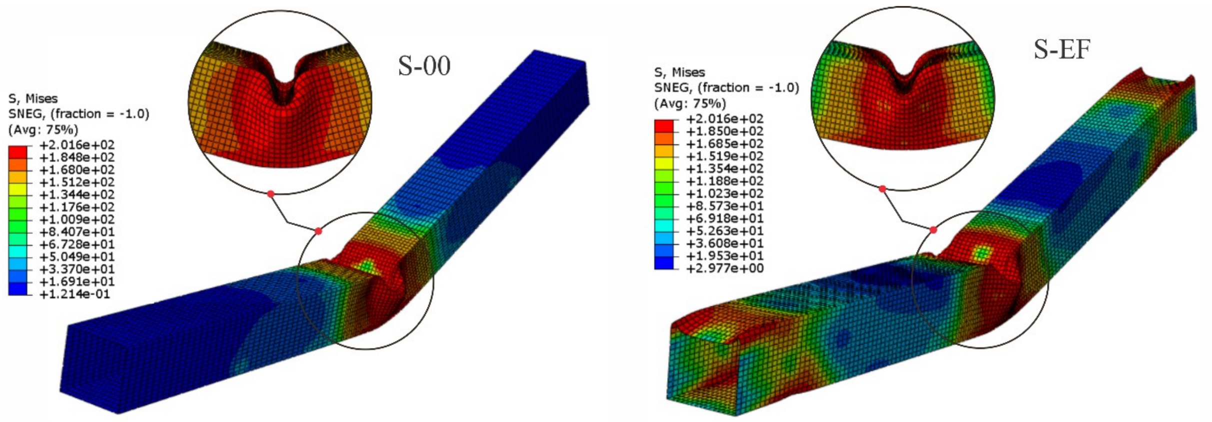

Figure 5. Final deformation mode at 50 mm of displacement I.

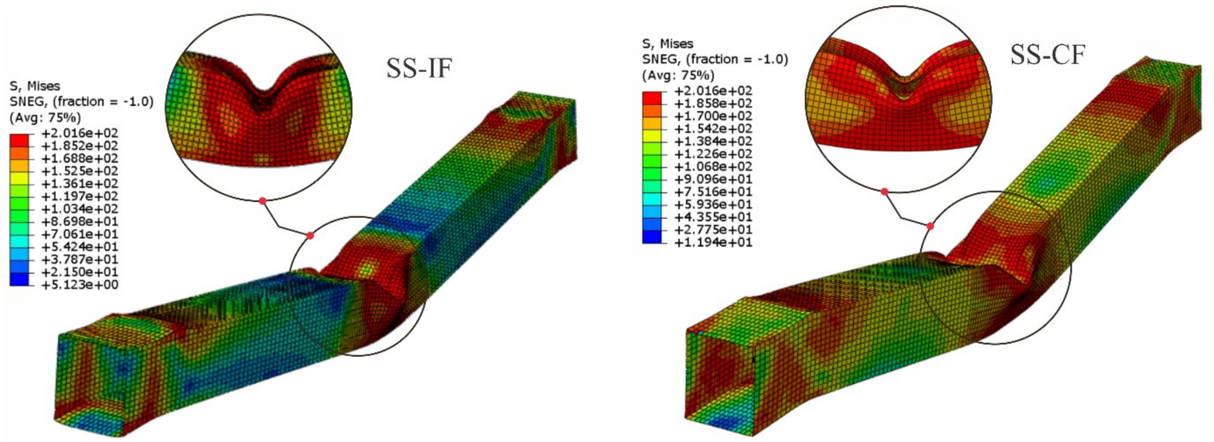

Figure. 6. Final deformation mode at 50 mm of displacement II.

The obtained results are shown in table 3. Accordingly, as the ends of the profile are fully constrained, an increase in P_{max} is obtained. The structure with internal and external friction (S-CF) presents the highest P_{max} value of 8.40 kN. This value represents an increase in 120% relative to the arrangement without friction (S-00). Meanwhile, the lowest value was computed by the structure with external frictional pads (S-IF) with 5.31 kN. In all cases, frictional fixtures improved the energy absorption capacity (E_a) in a range from 48.71% to 179.19%. The largest energy absorption capacity (419.96 J) is obtained when internal and external friction (S-CF) is generated at the ends of the profile. This improved behaviour was also reflected by calculating the highest mean force (P_m) and specific energy absorption (SEA) for S-CF with 8.40 kN and 1.448 J/g, respectively. This suggests higher resistance to the formation of travelling and stationary hinge lines during the bending process. Additionally, energy dissipated by friction effects and secondary hinge lines close to the ends were also observed.

Table 3. Summary of numerical results for the evaluated arrangements.

Code	P_{max} [kN]	P_m [kN]	E_a [J]	SEA [J/g]	CFE
SQ	6.09	3.01	150.42	0.518	0.49
S-EF	5.31	4.47	223.69	0.771	0.84
S-IF	8.51	6.22	310.96	1.072	0.73
S-CF	13.41	8.40	419.96	1.448	0.62

The effectiveness of the three frictional pads to improve the energy absorption capacity of a typical square profile has been confirmed. However, a large energy absorption capacity does not mean the best crashworthiness performance. To find the optimal behaviour of the arrangements, the crush force efficiency (CFE) is introduced in figure 7. Optimal performance is obtained when CFE is equal to 1. Considering the CFE value obtained for a typical profile (SQ), an increase in CFE from 26.53% to 71.47% was achieved by the arrangement with frictional pads.

According to Figure 7, and contrary to expectations, an increase in contact area of the frictional fixtures does not guarantee a better CFE performance. The combination of internal and external friction resulted in the poorest CFE (0.62). Despite the presence of the typical deformation at the middle section which is characterised by a central hinge line and two outward folds, a larger work was required to form the plastic hinges. Then, the maximum crush force was the highest, thus obtaining a lower CFE performance. On the other hand, external friction pads (S-EF) added resistance during the initial bending force, this resistance also contributed to generate frictional forces at the ends. Likewise, the ends not being fully constrained allowed the plastic deformation of the bottom edge of the beam’s ends, dissipating a large amount of energy with a relative low P_{max}. This contributed to achieving the best CFE of 0.84. The opposite case was observed for structures with internal and combined friction since an increase in E_a also increased the peak load. Thus, lower CFE values were obtained. Lastly, from our numerical findings presented in table 3 and figure 7, the use of friction as a secondary energy absorption mechanism was confirmed, especially when external friction is generated. Thus, this kind of arrangement (S-EF) should be considered for future mechanical designs of thin-walled absorbers.

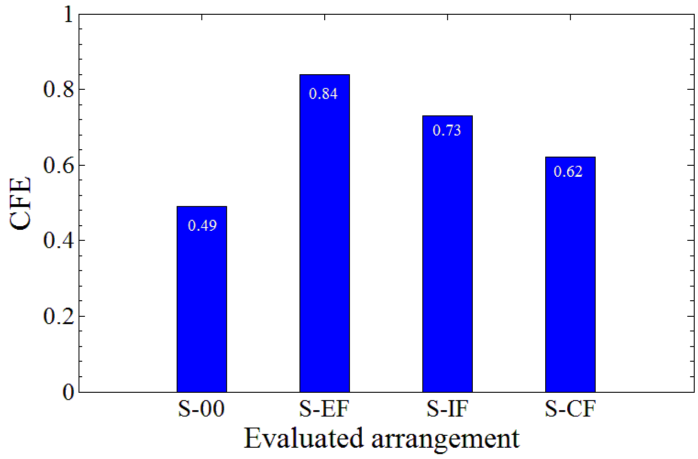

Figure 7. CFE of the four evaluated arrangements.

5. Conclusions
A numerical study of friction effect on crashworthiness performance of square profiles under bending load was carried out. The main objective of this article was to investigate the effectiveness of frictional pads to improve the crashworthiness and bending capacity of mechanical structures. From our numerical study we conclude:

1. Relative to a profile without friction (S-00), the use of frictional pads in any configuration increases the energy absorption capacity (E_a) in a range from 48.71% to 179.19%.
2. From figure 5-6 and table 3, the ability to dissipate energy is more a function of the constraint at the ends of the profile than of the contact area. This can be observed by comparing E_a for S-EF (223 J) and S-IF (310 J). In both cases, the arrangement presented the same friction contact area.
3. The use of frictional pads improves the total energy absorption capacity. However, it also induces an increase in peak load (P_{max}). Hence, when internal and external friction are generated at the same time, an increase in P_{max} up to 120% is computed with respect to a profile without friction (S-00).
4. Regard the CFE parameter, the best crashworthiness performance was obtained when external friction (S-EF) is generated at the ends of the profile. This condition obtained the highest CFE value of 0.84.
5. External friction forces add stiffness to the system and at the same time allows a secondary deformation at the ends. Then, a balance of P_{max} and E_a is obtained. From this mechanical behaviour configuration, S-EF could be used to counter the harmful effects of lateral crashes.

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