Coupled effect of thickness optimization and plastic forming history on crashworthiness performance of thin-walled square tube

Hasan Sofuoğlu1 · Salim Çam2

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Abstract
Thin-walled tubes are widely used as energy absorbers due to their high crashworthiness performance. This study aims to evaluate the effect of plastic forming history carried out for thickness optimization on crashworthiness performance of thin-walled square tube (TWST). Within the scope of the study, a series of numerical analyzes were conducted for the TWST using commercial finite element (FE) software. In order to determine the individual effect of optimization, the FG thickness of TWST was first obtained using LS-OPT software. Later, thickness gradient was achieved by performing a rolling process to consider individual plastic forming effects. Afterwards, a deep drawing process was carried out to shape TWST by considering springback and trimming effects. Finally, crash responses were obtained under axial high-velocity impact loading to determine the coupled effect of optimization and plastic forming on the crashworthiness performance of the TWST. It was determined that the coupled effect, which takes plastic forming and optimization effects into account, reduced the peak crush force of the TWST by 24% and increased the absorbed energy value by 39%. The results obtained from this study showed that coupled effect of optimization and plastic forming processes has a significant effect on the crashworthiness performance of the TWST, and otherwise, either overestimated or underestimated results are obtained.

Keywords Thin-walled square tube · Crashworthiness performance · Optimization · Plastic forming · Finite element analysis · Coupled effect

1 Introduction
Thin-walled structures have been used as energy absorbers for a long time and have attracted many researchers. Since then, an enormous amount of contribution has been made to the related field. Effect of tube geometry [1–4], material type [5, 6], filling materials [7–9] widely investigated by researchers. Moreover, advances in the manufacturing processes and a growing interest in engineering optimization allowed researchers to study more complex geometries [10, 11]. Thin-walled tubes with functionally graded (FG) thickness created to improve energy absorption efficiency and crush resistance performance are the product of these developments [12, 13].

Li et al. [14] compared different FG thickness on the crashworthiness of thin-wall tubes under multiple loading angles. They optimized the thin-walled tube using NSGA-II algorithm and concluded that graded thickness reduces the possibility of global bending. Zhang and Zhang [15] investigated effect of nonlinear thickness distribution considering conical tubes. They implemented tapering process to FE analyzes in order to obtain nonlinear thickness distribution. The results showed that the energy absorption capacity of the tubes increased by 120%. Sun et al. [16] studied effect of thickness gradient under axial impact load. They used a gradient exponent parameter to control thickness gradient and optimized thickness distribution. They stated that exponent parameter has considerable effect on the crashworthiness.
Another aspect related to the complex geometries is the effect of the manufacturing processes on the crash response. Lee et al. [17] performed crash simulations for side rail and hydro-formed tube considering forming history. They stated that forming history of components affects crash response considerably. Also, they emphasized that the use of coarser mesh yields equally good results when compared to finer mesh. Gao et al. [18] compared the crash responses for one-step forming and incremental forming. They explained that there is a considerable difference between two methods and concluded that incremental forming simulation provides more accurate results. Kumar and Shrivaathsav [19] investigated influence of forming parameters for capped cylindrical tubes. They stated that thickness variation and residual stress/strains originated from forming application improves impact performance of the tubes compared to tubes with constant thickness. Du et al. [20] proposed an inverse method for implementing stamping effect to the crash simulations. Considering side rail, they indicated that with regards to the simulation accuracy effective plastic strain is more important than thickness reduction. Niu et al. [21] compared the effect of the stamping and bending on crash performance. They observed progressive buckling for bent specimens and global instability for stamped specimens. Karagöz and Yıldız [22] optimized tube geometry using various optimization algorithms considering forming effects. They stated that forming process has considerable effect on the crash performance of the tubes. Doruk [23] investigated effect of steel processing effects on the crash performance of the automobile frontal bumper system. Bumper beam and energy absorbers produced considering effect of deep drawing, trimming, and springback. The results obtained showed that with counting effect of forming history, parts of bumper system absorbed 12.89% more energy. Effect of deep drawing for quasi-static axial crash was also studied by Gümrük and Karadeniz [24]. They concluded that whereas plastic strain and thinning affect the crash response, residual stress has limited effects.

Considering studies summarized above and many more published in the related field of the literature, it is evident that FG thickness improves the crash performance of the tubes. It is also clear from these studies that plastic forming methods affect the crash performance of the tubes considerably. However, to the best of the authors’ knowledge, the coupled effect of thickness optimization and the plastic forming method used to obtain thickness gradient has received no attention or study up to this point. Therefore, this study was carried out to investigate the effects of plastic forming history pursued thickness optimization on crashworthiness performance of the TWST, namely the coupled effect of optimization and plastic forming.

2 Materials and methods

This study consists of four stages: FG thickness optimization, rolling, deep drawing, and crush analysis. To perform these stages, a series of FE analyzes were conducted using commercial FE software, LS-DYNA. In the first phase of this study, the thickness of TWST was optimized using LS-OPT software to obtain the comparison results to be used in determining the coupled effect of optimization and plastic forming. The rolling process was then conducted to achieve the intended thickness gradient on the plate rather than directly importing optimized thickness values to the FE model. Later, deep drawing was applied to the plate having the desired thickness gradient after rolling to shape the thin-walled square tube. Finally, crush analysis under high-velocity impact load was carried out to determine the coupled effect of optimization and plastic forming on the crashworthiness performance of the TWST.

2.1 Finite element modeling

In this study, mild steel (E = 207 GPa, ν = 0.3) was used for energy absorber material [2]. The stress-strain values given as tabular data in reference 2 were arranged and given graphically in Fig. 1. Because of its strain rate sensitivity and suitability of crash modeling [3–5, 25], piecewise linear plasticity was selected for material model. Effect of the strain rate was implemented by activating VP (Formulation for rate effects) option which uses Cowper-Symonds constitutive model for crush analyzes.

![Fig. 1. True stress – plastic strain curve of the energy absorber material](image-url)
Cowper-Symonds equation is expressed by scaling two factors; strain and strain rate factors [26]:

\[
\sigma_y = 1 + \left( \frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}} \left( \sigma_0 + \beta E_p \varepsilon_{eff}^p \right)
\]

where \(\sigma_0\) is the initial yield stress, \(\dot{\varepsilon}\) is the strain rate, \(C\) and \(P\) are strain rate parameters. Also \(\beta\) represents the strain hardening parameter, \(\varepsilon_{eff}^p\) is the effective plastic strain and \(E_p\) is the plastic hardening modulus. A computational method was then proposed to determine the Cowper–Symonds parameters from a single Taylor test [27]. Later on, the following form of the equation was used to implement strain rate effects into FEA [28]:

\[
1 + \left( \frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}}
\]

Within the scope of the study the strain rate parameters \(C\) and \(P\) are selected as 6.844 \((ms)^{-1}\) and 3.91, respectively [29].

Figure 2 illustrates the base FE model for TWST. The base model of the TWST has a constant thickness of 1.5 mm and corresponds to a mass of 1 kg. In order to evaluate the effect of each segment’s thickness and to reduce the computational cost, the tube geometry was partitioned into 12 pieces to perform thickness optimization. The side length of the tube is 90 mm, while 240 mm is the total length. The TWST was meshed using a 5×5 mm Belytschko-Tsay shell element with five integration points through the thickness. The TWST is fixed from the bottom, and a solid-rigid wall with 100 kg mass impacts the tube with a speed of 54 km/h. According to UN Regulation No 137 [30], the impact speed was selected, suggesting a speed of 50 km/h or higher. For the contacts between lobes of the TWST and between the TWST and the rigid wall, automatic single surface contact algorithm was used. A constant friction coefficient of 0.2 was applied to all contact surfaces to prevent lateral movements [3, 7]. Also, the hourglass was controlled via control hourglass card.

### 2.2 Validation of the finite element model

Before proceeding with the actual analysis, it should be shown that the FE model created for the simulation performed in the current study is correct. Two finite element analyzes (FEA), namely mesh convergence and model validation studies, were conducted for this purpose. Three different element sizes of 1.25, 2.5, and 5 mm were evaluated to assess the effect of element size (Fig. 3). Also, for validation purposes, the FE model in the Nagel and Thambiratnam’s study [2] were reproduced and compared with those of the present study.

### 2.3 Thickness optimization

After carrying out the FEA of TWST with constant thickness, thickness optimization of the TWST was performed using LS-OPT software. For each section of the tube, a thickness parameter, a total of 12 parameters were defined, and the mass of the tube, absorbed energy, and peak crushing force (PCF) was calculated. LS-OPT offers six different metamodeling techniques, namely, Polynomial, Sensitivity, Feed Forward Neural Network (FNN), Radial Basis Function Network (RBFN) and Kriging. However, when using polynomial-based response surfaces, the user has to choose the order of the polynomial, and there is a significant possibility of bias error [31]. Meanwhile, Kriging has fitting problems [32] and considerably sensitive to noise [33]. Distinctly, RBFN and FNN have not serious deficiencies, and they are similar in terms of accuracy. Moreover, it is known that FNN is better than RBFN for some problems [34]. In this study, thickness values were therefore determined by the FNN method to maximize absorbed energy and 1/PCF. For each thickness, 20 simulation points with a space-filling scheme were selected. Also, considering the result obtained from the TWST with
constant thickness, the mass of the tube was constrained by 1 kg while the PCF between 0 and 5 ms was constrained by 240 kN. Figure 4 shows the flowchart of the optimization process.

2.4 Plastic forming

Even if there is quite an improvement in the crashworthiness performance of the TWST after the optimization process, the results would be fallacious without considering the effects of the manufacturing processes to obtain the thickness gradient and form of the tube. However, the results given in most of the literature have been obtained without considering the effects of the manufacturing processes used in the optimization method. Therefore, the validity of the results obtained in this way for the crashworthiness performance of the TWST can be questionable.

The most convenient and economical manufacturing process to achieve graded thickness is rolling. However, it is not possible to produce the TWST as a whole with a rolling process. For this reason, after achieving variable thickness via rolling, the tube geometry was produced in two parts by the deep drawing process. As a result, rolling and deep drawing processes were sequentially performed to investigate the coupled effect of optimization and plastic forming on the TWST’s crashworthiness performance in this study. Subsequently, these two parts were welded to form the square tube for crush analysis. Each forming analysis connected via dynain file until crush analysis of the tube, including stress and strain distributions.

2.4.1 Rolling

Two dimensional FE model of the rolling was constructed as shown in Fig. 5. Both rolls and workpiece were meshed using plane strain elements. In order to reduce complexity, the workpiece kept constant while the movement was applied to the rolls with the boundary prescribed motion rigid keyword. The rolls were modeled as rigid, and piecewise linear plasticity material model was used for the workpiece. For
the contacts between rolls and the workpiece 2D automatic surface to surface contact algorithm was utilized. Since rolls were not rotating, the friction coefficient between the rolls and the workpiece was considered to be zero in order to simulate the rotating effect.

The thickness of the plate was initially 2.5 mm. Considering thickness values obtained from multiobjective optimization, the workpiece was partitioned into 12 sections. The length of each section was determined concerning the conservation of volume. Maximum thickness reduction was limited to 40% for a single pass, and multiple passes were applied to the sections to obtain the required thickness. To control thickness reduction, contact between the rolls and the workpiece was only activated for the related section of the workpiece. Moreover, since deep drawing is the subsequent three-dimensional process the workpiece was reconstructed using shell elements after two-dimensional rolling analysis. The workpiece was then transferred to the deep drawing process.

2.4.2 Deep drawing

The deep drawing process was used to produce half of the TWST from the plate with graded thickness. The finite element model of the deep drawing consists of four parts: Workpiece, punch, die, and binders. A schematic illustration of the deep drawing process is given in Fig. 6.

A trapezoidal punch velocity profile with a maximum speed of 2 mm/ms was used in the deep drawing process, as given in Fig. 7. Tool motion was defined by using the boundary prescribed motion rigid keyword.

All parts meshed with the Belytschko-Tsay shell element and 5 integration points through the thickness of the workpiece were utilized. Using the control shell keyword, shell
element thickness change and warping stiffness were activated. A stiffness type of hourglass control implemented to the FE model with the control hourglass keyword. The punch, the die, and binders were modeled as rigid, while for workpiece piecewise linear plasticity material model was used. Contacts between the workpiece and other parts created using forming one way surface to surface contact algorithm with a friction coefficient of 0.1. Shell thickness offsets were activated with control contact keyword excluding rigid bodies. The workpiece meshed with 5×5 mm elements and adaptive mesh refinement activated by the adopt flag in the part keyword. Finally, springback analysis was established using the interface springback seamless keyword. After springback analysis, surplus sections of the workpiece were trimmed using the element trim keyword.

2.5 Crush analysis

In this section, crash analysis was carried out by considering the coupled effects of optimization and plastic forming. Prior to this section, the thickness gradient of TWST was achieved by performing the rolling process, while the deep drawing process was then used to form the tube geometry. After rolling and deep drawing processes, the tube configuration has minor changes due to the nature of the forming processes, e.g., the corners of the tube are smooth due to the deep drawing process. By performing the deep drawing process, there are now two symmetric half-tubular parts with graded thickness to build up TWST as shown in Fig. 8. These two symmetric parts were then connected using 22 spot welds. Spot welds were modeled using the constrained spot weld keyword and considered as rigid. Failure of the spot welds has not been taken into account in this study. The FE model was the same as the base FE model given above.

3 Results

3.1 Convergence and validation results

The results of the mesh convergence studies were given in Fig. 9. For each element size, the crush force-crush displacement curves showed a good agreement except for small fluctuations through the end, and more importantly, the PCFs are nearly identical. Similarly, the absorbed energy versus crush displacement plots initially follows almost the same path; although there is a deviation toward the end of the process. Therefore, it has been shown that the FE model is not affected by the element sizes tested in this study. In addition to this, the validation results of the FE model were shown in Fig. 10. While the results were in perfect harmony for the crush force at the beginning of the process (PCF), this consistency decreased at the end, showing slight fluctuations. This can be attributed to usage of the different commercial finite element software from the reference study and can be negligible. Moreover, the higher frequency of the data used in the current study to establish the graph can be another possible reason. After the convergence and verification studies, it was concluded that the FE model created could be used in the studies that constitute future stages of this research.

3.2 Base TWST results

Before thickness optimization, the FEA of TWST was performed with a constant thickness of 1.5 mm for subsequent comparison studies (will be named as single-piece tube). As
can be seen from Fig. 11 that the preliminary results for the TWST with constant thickness were obtained to be 240 kN and 9.9 kJ for the PCF and the absorbed energy, respectively.

### 3.3 Thickness optimization results

Figure 12 shows the scatter plot of the optimization results. The optimum thickness values of the TWST obtained from multiobjective optimization are given in Table 1, while Fig. 13 shows the crush responses obtained from the FEA of the optimized model.

As can be seen from Fig. 13 that the optimized model showed a significant improvement in the PCF and absorbed energy. While the PCF was obtained as 150 kN with a 37.5% decrease, the amount of absorbed energy increased by 18% to 11.68 kJ. However, after 100 mm of deformation, the crush force of the optimized TWST starts to rise and exceeds the PCF of the TWST with constant thickness after 130 mm. This is inevitable behavior due to the nature of the TWST with graded thickness. If the thickness of the tube is constant, the crash force shows only small peaks afterwards of deformation initiation. However, for the optimized tube, deformation initiates from the thinner section of the tube (t2–t7), and the crush force does not make another considerable peak until the thinner section completely deforms (Fig. 14). With the increased thickness sections of the TWST (t8–t12), more force is needed to initiate new deformation.

### 3.4 Plastic forming results

The rolling analysis was performed to obtain gradient thickness. These values for each section of the workpiece after rolling were shown in Table 2 and showed good agreement with the optimum thickness values listed in Table 1.

After rolling, the workpiece was transferred to the deep drawing analysis. Fig. 15 depicts the workpiece’s effective plastic strain values acquired from the springback analysis for deep drawing analysis, while Fig. 16 shows the workpiece’s final form after trimming.

### 3.5 Crush analysis results with coupled effect

The thickness distribution and the residual plastic strains of the tube prior to crush analysis are given in Fig. 17.
Although the geometry of the built-up TWST, named the two-piece tube, did not change significantly compared to single-piece TWST, FE analyzes were rerun to make accurate comparisons. Figure 18 shows the plastic forming effect only by comparing the results of the single-piece and two-piece tubes with constant thickness. Due to smooth corners, the values of PCF and total absorbed energy dropped from 240 to 215 kN and 9.9 kJ to 9.5 kJ. This proves that the crush performance of TWST decreased by 9% and 4% for the PCF and the absorbed energy, respectively, by taking the plastic forming effect only into account. In addition to this, the results showing only the optimization effect in one-

### Table 1

| Optimum thickness values (mm) |  
|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |
| 2.26 | 0.96 | 1.13 | 1.73 | 1.78 | 2.41 | 2.29 |
piece and two-piece tubes with graded thickness were given in Fig. 19. The PCF decreased from 150 to 139 kN, while the total amount of absorbed energy also dropped from 11.68 to 10.4 kJ from the single-piece tube to the two-piece tube, respectively. This decrease in the PCF and the absorbed energy corresponds to 7% and 11%, respectively, and corresponds to the optimization effect only. As can be deduced from the results given above, considering the individual effect of optimization

Fig. 13. Optimization effect on the crashworthiness performance of the FG-TWST

Fig. 14. Deformation of the single-piece tube with a constant thickness, b optimized thickness
and plastic forming gives erroneous results about the crashworthiness performance of TWST.

Therefore, the final stage of this study has been carried out by using the two-piece tube to assess the coupled effect of optimization and plastic forming history on the TWST with graded thickness. More precisely, Figs. 20 and 21 were included to clearly illustrate the coupled effect of rolling and deep drawing on the crashworthiness performance of the two-piece tube with optimized thickness. Moreover, the results were also listed in Table 3 for clarity.

It is very clear from the figures that considering only the optimization effect, the obtained PCF and the absorbed energy were 139 kN and 10.4 kJ, respectively. After the optimization process of the two-piece tube, the PCF decreased by 35% (215 to 139 kN), and the amount of absorbed energy increased by 9% (9.5 to 10.4 kJ). Even if there is quite an improvement in the crashworthiness performance of the TWST after the optimization process, this result does not involve the effect of the forming processes to achieve gradient thickness and to form the tube. With the introduction of the coupled effect, which took the plastic forming effect into account, the PCF and the absorbed energy obtained as 164 kN and 13.2 kJ, respectively. That is; PCF decreased by 24% (215 to 164 kN), and the amount of absorbed energy increased by 39% (9.5 to 13.2 kJ). These results clearly demonstrate the importance of the plastic forming process. Moreover, when the plastic strains related to the forming processes are not considered, the PCF and the absorbed energy differ by 18% and 27%, respectively.

| Table 2 Thickness distribution of the workpiece after rolling process |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Thickness values (±0.02 mm) |
| \( t_1 \) | \( t_2 \) | \( t_7 \) | \( t_8 \) | \( t_9 \) | \( t_{10} \) | \( t_{11} \) | \( t_{12} \) |
| 2.28 | 0.98 | 1.14 | 1.74 | 1.78 | 2.40 | 2.32 |

4 Conclusion

In this study, the combined effects of rolling and deep drawing processes were investigated via the FE method. Initially, the FG thickness of the TWST was obtained using LS-OPT software with the FNN method. The rolling process, among others, was selected to achieve graded thickness geometry of the TWST, while a deep drawing process was performed to obtain the square tube form. The coupled effect of optimization and plastic forming on the crashworthiness performance of the TWST was then studied. Based on the results, the following conclusions were reached:

- The multiobjective optimization program overestimates the PCF and the absorbed energy. More precisely, the PCF showed a 37.5% decrease (from 240 to 150 kN) while the amount of absorbed energy increased by 18% from 9.9 to 11.68 kJ.
- As for the plastic forming effect only, both parameters were underestimated. For example, the PCF decreased from 240 to 215 kN, and the absorbed energy also reduced from 9.9 to 9.5 kJ.
Fig. 17. The thickness and the residual plastic strain distribution of the TWST

Fig. 18. Plastic forming effect only on the crashworthiness performance of TWST with constant thickness of 1.5 mm
After the optimization process of the tube, the PCF decreased by 35% (215 to 139 kN), and the amount of absorbed energy increased by 9% (9.5 to 10.4 kJ). Finally, with the implementation of the plastic forming processes, the PCF decreased by 24% (215 to 164 kN), and the amount of absorbed energy increased by 39% (9.5 to 13.2 kJ).

The results of this study, therefore, showed that the coupled effect of optimization (rolling) and plastic forming (deep drawing) has a significant effect on the crashworthiness performance of the TWST. It was also determined that considering optimization and plastic forming effects individually resulted in either overestimated or underestimated findings. Neglecting the coupled effect inevitably leads to considerable differences in the crashworthiness performance of the TWST and will have negative consequences in, such as, automotive industry. Therefore, it should be noted that both the thickness optimization obtained without considering the plastic forming effect and the plastic forming effect obtained without considering the thickness optimization should not be used to evaluate the crashworthiness performance of the energy absorber tubes.

Fig. 19. Optimization effect only on the crashworthiness performance of TWST

Fig. 20. Effect of plastic forming on TWST with optimized thickness
Authors contributions This manuscript is the original work of all authors. The authors declare that all authors were fully involved in the study and preparation of the manuscript.

Data Availability The data and materials supporting the results of this article are included within the article.

Declarations

Ethical approval The authors declare that there are no conflicts with the ethical standards by Springer and the research conducted in context of this research paper.

Consent to participate No research involving human subjects has been conducted in context of this publication and thus, a consent to participate is not needed.

Consent to publish No research involving private companies has been conducted in context of this publication and thus, a consent to publish is not needed.

Competing interests The authors declare no competing interests

References

1. Abramowicz W, Jones N (1986) Dynamic progressive buckling of circular and square tubes. Int J Impact Eng 4:243–270. https://doi.org/10.1016/0734-743X(86)90017-5
2. Nagel GM, Thambiratnam DP (2004) A numerical study on the impact response and energy absorption of tapered thin-walled tubes. Int J Mech Sci 46:201–216. https://doi.org/10.1016/j.ijmecsci.2004.03.006
3. Reddy S, Abbasi M, Fard M (2015) Multi-cornered thin-walled sheet metal members for enhanced crashworthiness and occupant protection. Thin-Walled Struct 94:56–66. https://doi.org/10.1016/j.tws.2015.03.029

Fig. 21. Comparison for all effects

| Tube type                                | Type   | Peak crush force (kN) | Absorbed energy (kJ) |
|------------------------------------------|--------|------------------------|-----------------------|
| Single-piece tube with constant thickness| SPCT   | 240                    | 9.9                   |
| Two-piece tube with constant thickness   | TPCT   | 215                    | 9.5                   |
| Two-piece tube with graded thickness only| TPGT   | 139                    | 10.4                  |
| Two-piece tube with graded thickness and forming | TPGTF  | 164                    | 13.2                  |

Table 3 Comparison of all effects
4. Tran TN (2017) Crushing analysis under multiple impact loading cases for multi-cell triangular tubes. Thin-Walled Struct 113:262–272. https://doi.org/10.1016/j.twss.2017.01.013
5. Smerd R, Winkler S, Salisbury C, Worswick M, Lloyd D, Finn M (2005) High strain rate tensile testing of automotive aluminum alloy sheet. Int J Impact Eng 32:541–560. https://doi.org/10.1016/j.ijimpeng.2005.04.013
6. Itabashi M, Kawata K (2000) Carbon content effect on high-strain rate tensile properties for carbon steels. Int J Impact Eng 24:117–131. https://doi.org/10.1016/S0734-743X(99)00050-0
7. Gedikli H, Meric D (2016) Energy absorption behavior of tailor-welded tapered tubes under axial impact loading using coupled FEM/SPH method. Thin-Walled Struct 104. https://doi.org/10.1016/j.twss.2016.03.002
8. Coelho RM, Alves de Sousa RJ, Fernandes FAO, Teixeira-Dias F (2013) New composite liners for energy absorption purposes. Mater Des 43:384–392. https://doi.org/10.1016/j.matdes.2012.07.020
9. Ahmad Z, Thambiratnam DP (2009) Dynamic computer simulation and energy absorption of foam-filled conical tubes under axial impact loading. Comput Struct 87:186–197. https://doi.org/10.1016/j.compstruct.2008.10.003
10. Costas M, Diaz J, Romera L, Hernandez S (2014) A multi-objective surrogate-based optimization of the crushworthiness of a hybrid impact absorber. Int J Mech Sci 88:46–54. https://doi.org/10.1016/j.ijmecsci.2014.07.002
11. Gedikli H (2013) Crashworthiness optimization of foam-filled tailor-welded tube using coupled finite element and smooth particle hydrodynamics method. Thin-Walled Struct 67:34–48. https://doi.org/10.1016/j.twss.2013.01.020
12. Zhang X, Zhang H, Wen Z (2015) Axial crushing of tapered circular tubes with graded thickness. Int J Mech Sci 92:12–23. https://doi.org/10.1016/j.ijmecsci.2014.11.022
13. Zhang X, Wen Z, Zhang H (2014) Axial crushing and optimal design of square tubes with graded thickness. Thin-Walled Struct 84:263–274. https://doi.org/10.1016/j.twss.2014.07.004
14. Li G, Zhang Z, Sun G, Huang X, Li Q (2015) Comparison of functionally-graded structures under multiple loading angles. Thin-Walled Struct 94:334–347. https://doi.org/10.1016/j.compstruct.2015.04.030
15. Zhang H, Zhang X (2016) Crashworthiness performance of conical tubes with nonlinear thickness distribution. Thin-Walled Struct 99:35–44. https://doi.org/10.1016/j.twss.2015.11.007
16. Sun G, Xu F, Li G, Li Q (2014) Crashing analysis and multiobjective optimization for thin-walled structures with functionally graded thickness. Int J Impact Eng 64:62–74. https://doi.org/10.1016/j.ijimpeng.2013.10.004
17. Lee SH, Han CS, Oh SI, Wriggers P (2001) Comparative crash simulations incorporating the results of sheet forming analyses. Eng Comput 18:744–758. https://doi.org/10.1108/EUM0000000005786
18. Gao R, Xi C, Tyan T, Mahadevan K, Doong J (2009) A practical approach to consider forming effects for full vehicle crash application. SAE Tech. Pap. https://doi.org/10.4271/2009-01-0471
19. Praveen Kumar A, Shrivastavas S (2019) Influence of forming parameters on the crash performance of cabled cylindrical tubes using LS-DYNA follow-on simulations. Int J Interact Des Manuf 13:1215–1232. https://doi.org/10.1007/s12008-019-00552-z
20. Du H, Ye P, Wang D, Tang X (2010) Study on accuracy improvement of vehicle crash simulation considering stamping effects. Adv Mater Res 139–141:532–535. https://doi.org/10.4028/www.scientific.net/AMR.139.141.532
21. Niu J, Zhu P, Guo Y (2010) Crash performance of top-hat tubular structures considering different forming conditions. Adv Mater Res 139–141:571–575. https://doi.org/10.4028/www.scientific.net/AMR.139.141.571
22. Karagöz S, Yıldız AR (2017) A comparison of recent metaheuristic algorithms for crashworthiness optimisation of vehicle thin-walled tubes considering sheet metal forming effects. Int J Veh Des 73:179–188. https://doi.org/10.1504/IJVD.2017.082593
23. Doruk E (2017) Steel processing effects on crash performance of vehicle safety related applications. Steel Compos Struct 24:351–358. https://doi.org/10.1016/j.scms.2017.24.351
24. Gümrük R, Karadeniz S (2009) The influences of the residual forming data on the quasi-static axial crush response of a top-hat section. Int J Mech Sci 51:350–362. https://doi.org/10.1016/j.ijmecsci.2009.03.010
25. Zhang X, Zhang H, Ren W (2018) Axial crushing of tubes fabricated by metal sheet bending. Thin-Walled Struct 122:252–263. https://doi.org/10.1016/j.twss.2017.09.023
26. G.R. Cowper, P.S. Symonds, Strain hardening and strain-rate effects in the impact loading of cantilever beams, 1957.
27. Hernandez C, Maranon A, Ashcroft IA, Casas-Rodriguez JP (2013) A computational determination of the Cowper-Symonds parameters from a single Taylor test. Appl Math Model 37:4698–4708. https://doi.org/10.1016/j.apm.2012.10.010
28. LS-DYNA Keyword User’s Manual Volume II (2018) Material Models. Livermore Software Technology Corporation, California
29. Guler MA, Cerit ME, Bayram B, Gercceker B, Karakaya E (2010) The effect of geometrical parameters on the energy absorption characteristics of thin-walled structures under axial impact loading. Int J Crashworthiness 15:377–390. https://doi.org/10.1080/13588260903488750
30. UN Regulation No 137 Uniform provisions concerning the approval of passenger cars in the event of a frontal collision with focus on the restraint system (2020) 18–61.
31. Standen N, Roux W, Basudhar A, Eggleston T, Goel T, Craig K (2015) LS-OPT User’s manual: a design optimization and probabilistic analysis tool for the engineering analyst. Livermore Software Technology Corporation, California
32. Xu QS, Liang YZ, Fang KT (2000) The effects of different experimental designs on parameter estimation in the kinetics of a reversible chemical reaction. Chemom Intell Lab Syst 52:155–166. https://doi.org/10.1016/S0169-7439(00)00084-8
33. Jin R, Chen W, Simpson TW (2001) Comparative studies of metamodelling techniques under multiple modelling criteria. Struct Multidiscip Optim 23:1–13. https://doi.org/10.1007/s00158-001-0160-4
34. N. Standen, T. Goel, Metamodel sensitivity to sequential adaptive sampling in crashworthiness design, in: 12th AIAA/ISSMO Multidiscip. Anal. Optim. Conf., 2008.

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