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A New Type of Energy Absorbing Structural Component: Spiral Thin-Walled Tube

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Abstract. Various thin-walled (TW) tubular components have been widely applied to absorb impact energy due to their sound crashworthiness and long stroke. This paper presents a novel spiral TW tubular component used for absorbing energy. The presented TW structural component is easily prepared and cost-effective because it can be handily manufactured by sheet metal rolling. Its geometry structure on cross section is spiral so it is called spiral TW tube in this work, which was studied by formulation method. Furthermore, its dynamic crushing and energy absorbing characteristics under impact loading was investigated by means of simulation analysis. The analysis result shows that the presented spiral TW tube has a superior energy absorbing performance and is promising used in passive safety area.

1. Introduction

Thin-walled (TW) tubular parts or components have big advantages in lightweight and crashworthiness and have been widely used in automotive, aerospace, transportation and defense industries. On one hand, wide application of lightweight TW tubular components in transport industry can save weight and reduce CO₂ emissions. On the other hand, sound crashworthiness of the TW tubular components can effectively absorb impact force of a serious crash and reduce death or injury risk of occupants. Therefore, studies concerning the TW tubular components have become increasingly attractive in recent years.

The structures of the traditional TW tubular components used for absorbing energy are various, mainly including TW circular structure, square structure, corrugated tubular structure, tapered circular structure and so on. Enormous investigations into the crashworthiness and energy absorbing performance of all kinds of the traditional TW tubular components have been carried out in the past decades [1]. Especially, as the most common structure, the axial crushing behaviors of the TW circular tubes were studied early [2]. It was revealed that the deformation mode of the TW circular tubes principally depends on their geometric parameters, which includes the so called concertina or ring mode, diamond mode, Euler mode and so on [2, 3]. By contrast, as another common TW structural tube, the crashworthiness and energy absorbing capacities of the TW square tubes have been also investigated in recent years. The studies about the TW square tubes with various cross-sectional shapes were carried out, including multi-corner [4, 5], multi-cell [6, 7], foam-filled [8] and so on. Meanwhile, the TW structural tubes with other cross sectional shapes such as multi-cell hexagonal tubes were also studied [9].

Furthermore, as far as axial direction structure is concerned, some investigations involved the TW tubes with functionally graded thickness (FGT), such as TW square tubes with FGT [10, 11] and TW



tapered circular tubes FGT [12-14]. In addition, TW corrugated tubes also have non-uniform thicknesses in axial direction which were studied by some researchers [15-17].

Besides the traditional TW structural tubes, a kind of folded square tube which can be fabricated by sheet metal bending has recently excited interest [18, 19]. This kind of folded tube is easily prepared, cost-effective and flexible in sectional shape, so is promising to be used in many engineering fields. Especially, the crashworthiness of the folded tube is also a concern. For example, Zhang et al. investigated side bending collapse [18] and axial crushing [19] of the folded square tubes, respectively. However, it is a pity that the related studies are barely concerned with the folded tubes with square structure at present.

By contrast, this paper presents an investigation into a new kind of energy absorbing structural component, called spiral TW tube in this work, which is concerned with its manufacturing process, geometry structure, dynamic crushing and energy absorbing characteristics undergoing impact loading. As a lightweight and promising energy absorbing structural tube, this novel spiral TW tube can be potentially used for passive safety field. Furthermore, the fabricating cost of this kind of spiral TW tube is relatively lower because it can be easily obtained by sheet metal bending (or called sheet metal rolling, more exactly). The geometry structure of the spiral TW tube was studied via formulation method in this work. In addition, the axial crushing and energy absorption characteristics was investigated by means of simulation analysis. The analysis results show that the spiral TW tubes have a sound energy absorbing performance and a great potential applied to act as energy absorber. So to say, this work provides a new idea for passive safety study to some extent.

2. Manufacturing process and geometry structure

2.1. Manufacturing process

The spiral TW tube can be easily manufactured by sheet metal rolling. Especially, just one cylindrical bar with a certain diameter can serve as the mold, thus it is easily prepared and cost-effective. The manufacturing process is simply as follows: at first, roll the blank sheet metal round the mold with desired turns into the spiral TW tube, as shown in Fig. 1, and then, draw the mold out from the rolled spiral TW tube. It should be noted that, however, elastic springback would be very likely to occur if the rolled spiral TW tube is loosened immediately. So some measures should be taken to deal with the springback issue this moment.

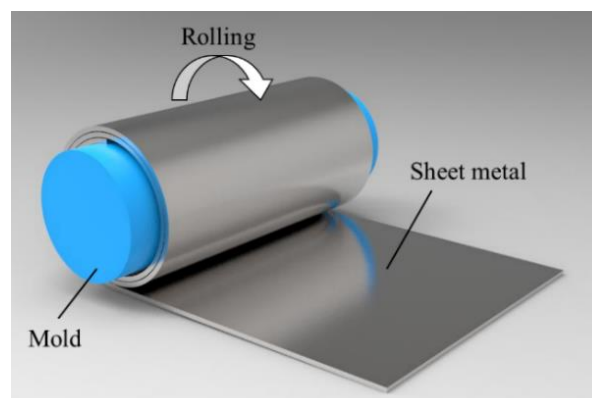


Figure 1. Manufacturing process of the spiral thin-walled tube by sheet metal rolling.

In fact, the springback can be prevented effectively if the sheet metal end is fixed by welding or gluing before loosening. Accordingly, there are three contact modes at the sheet metal end after rolling the sheet metal, i.e. welding, gluing and free contact, as shown in Fig. 2. In this work, laser welding is recommended for welding the sheet metal end due to simplification. The laser focus only need to aim at a point of the end and move long the end line of the sheet metal to weld the end fixedly. Therefore, there is a contact line along the sheet metal end if laser welding is used, as shown in Fig. 2(a). On the other hand, if the sheet metal end is fixed by gluing, there will be an adhesive layer at the contact area,

as shown in Fig. 2(b). In this work, the springback is thought to be prevented effectively if the sheet metal end is welded or glued together.

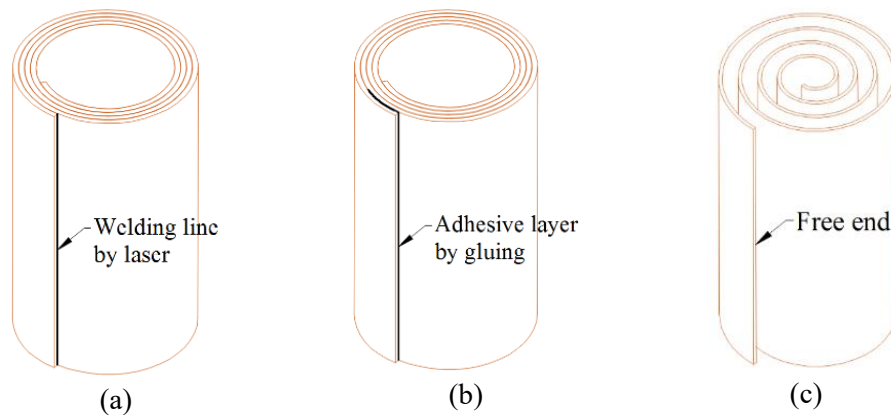


Figure 2. Contact modes of the sheet metal end after rolling.

With regard to the free contact mode of the sheet metal end (Fig. 2 (c)), the effect of the elastic springback cannot be neglected. The springback issue will inevitably lead to a certain structural or dimensional error in the final spiral TW tube. The extent of springback is related to the material of the sheet metal. Once the material is determined, the springback property should be considered and some measures must be taken to reduce the extent of springback as far as possible. For example, roll the tube round the mold repeatedly before pull the mold out from the rolled spiral TW tube. Or even, since the size (e.g. the outer diameter) of the spiral TW tube would be enlarged after springback, it would be better to appropriately decrease the diameter of the mold in advance so as to achieve the desired size of the final spiral TW tube after springback.

2.2. Geometry structure

From the view of cross section, the center line of the spiral TW tube is an Archimedean spiral, as shown in Fig. 3. Obviously, this Archimedean spiral center line is actually equal to the length of the sheet metal used for manufacturing the spiral TW tube. Therefore, in order to manufacture a desired spiral TW tube, the required length of the sheet metal can be worked out only need to calculate the length of the Archimedean spiral center line on the cross section. However, the calculation of the real length of the Archimedean spiral is rather complicated because an integral formula for calculating arc length in polar coordinates has to be used. Hence, for simplification, the required length of the sheet metal used for manufacturing the spiral TW tube is calculated by approximate method in this work and discussed as follows:

As we know, the mathematical equation of the Archimedean spiral in polar coordinates is $r = a + b\theta$, where θ is polar angle which indicates the total rolled degree of the Archimedean spiral; a is polar radius when $\theta = 0^\circ$; b is Archimedean spiral coefficient which indicates the increment of the polar radius when the spiral rolls 1 degree.

At first, let's discuss the case without springback. As shown in Fig. 3, the spiral TW tube is obtained by rolling the sheet metal with n turns plus a remnant length of k . The length of the spiral generated by every turn is approximately equal to the center line length of the annulus which envelop this corresponding spiral. For instance, the length of the spiral generated by i th turn, i.e. $\widehat{ABCDE}$ shown in Fig. 4, is approximately equal to the center line length of the annulus between the circles of which the radii are r_{i-1} and r_i , respectively. Accordingly, the total length of the sheet metal used for manufacturing the spiral TW tube can be calculated approximately by summing all the lengths of the center line of the annulus after n turns, of course, plus a remnant length of k .

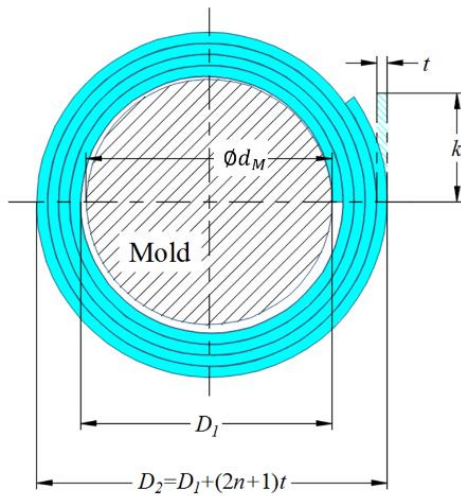


Figure 3. Cross sectional geometry structure of spiral thin-walled tube ($\Delta t = 0$).

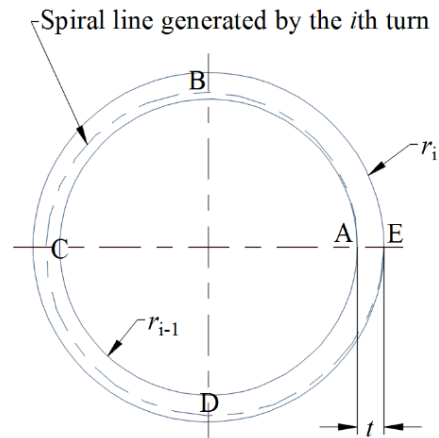


Figure 4. Schematic calculation method of spiral length of the i th turn.

Concretely speaking, according to the Archimedean spiral equation in polar coordinates, the radii of the circles which encircle the annulus enveloping the spiral of the i th turn (Fig. 4) can be respectively obtained by

$$r_i = a + 2\pi ib \quad (1)$$

$$r_{i-1} = a + 2\pi(i-1)b \quad (2)$$

Thus, the radius of the center line of the annulus enveloping the spiral of the i th turn can be calculated by

$$\bar{r}_i = \frac{r_i + r_{i-1}}{2} = a + 2\pi ib - \pi b \quad (3)$$

As the above mention, the length of the spiral generated by i th turn is approximately equal to the center line length of the corresponding annulus, which is calculated as

$$l_i \approx 2\pi\bar{r}_i = 2\pi(a + 2\pi ib - \pi b) \quad (4)$$

Therefore, the total spiral length of the spiral TW tube on the cross section is obtained by

$$L \approx \sum_{i=1}^n l_i = 2\pi \left(an + 2\pi b \sum_{i=1}^n i - \pi bn \right) + k \quad (5)$$

where, n is the total turn number of the spiral TW tube; k is the extra length after the n th turns. In addition, since $\sum_{i=1}^n i = n(n+1)/2$, the above equation can be modified as

$$L \approx 2\pi n(a + \pi bn) + k \quad (6)$$

From Fig. 3, it can be deduced that there are three relational expressions as follows:

$$D_1 = d_M + \pi b \quad (7)$$

$$a = \frac{d_M}{2} \quad (8)$$

$$b = \frac{t}{2\pi} \quad (9)$$

where, D_1 is the inner diameter of the spiral TW tube; d_M is the diameter of the mold; t is the thickness of the sheet metal.

Based on the above relational expressions (7), (8) and (9), the Eq. (6) can be modified as

$$L \approx \pi n \left(D_1 + nt - \frac{t}{2} \right) + k \quad (10)$$

Since the outer diameter of the spiral TW tube D_2 can be obtained by $D_2 = D_1 + (2n + 1)t$ shown in Fig. 3, the Eq. (10) also can be expressed as

$$L \approx \pi n \left(D_2 - nt - \frac{3t}{2} \right) + k \quad (11)$$

Both the equations (10) and (11) can be used to approximately calculate the required length of the sheet metal for manufacturing the spiral TW tube. Generally speaking, using Eq. (11) is more convenient because the outer diameter of the spiral TW tube D_2 can be measured directly and conveniently. It should be noted that the Eq. (10) or (11) was derived by the approximate method which the length of the spiral on every turn is approximately equal to the center line perimeter of the corresponding annulus, which means every turn would generate a calculating error. Therefore, the greater the turn number, the larger the cumulative calculating error will be.

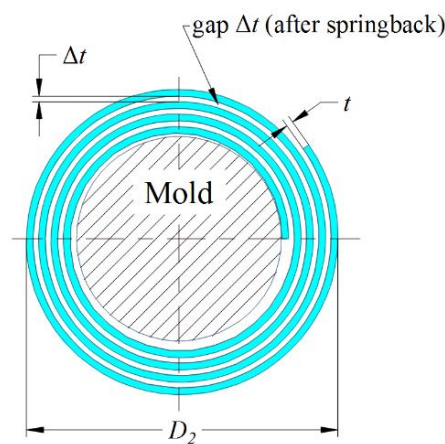


Figure 5. Cross sectional geometry structure of spiral thin-walled tube ($\Delta t \neq 0$).

If springback occur, there will be a certain gap among the coils, as shown in Fig. 5. Supposing that the gap among the spiral wall after springback is even and marked by Δt , the total spiral length of the spiral TW tube after springback on the cross section also can be calculated by using Eq. (10) or (11) only need to replace the parameter t with $t + \Delta t$ in the equation, such as:

$$L \approx \pi n \left[D_2 - n(t + \Delta t) - \frac{3(t + \Delta t)}{2} \right] + k \quad (12)$$

With regard to the value of the gap among the spiral wall after springback, a calculation method is given as follows:

In the light of Eq. (9), the Archimedean spiral coefficient after springback can be obtained by

$$b = \frac{t + \Delta t}{2\pi} \quad (13)$$

Based on Eqs. (7) and (13), the inner diameter of the spiral TW tube can be calculated by

$$D_1 = d_M + \frac{t + \Delta t}{2} \quad (14)$$

According to the relation of the inner and the outer diameters (shown in Fig. 3), the outer diameter of the spiral TW tube D_2 can be worked out by

$$D_2 = d_M + (2n + 1)t + (2n - 1)\Delta t + \frac{\Delta t}{2} \quad (15)$$

Therefore, based on the above equation, the value of the gap among the spiral wall after springback can be obtained by

$$\Delta t = \frac{D_2 - d_M - (2n + 1)t}{2n - 0.5} \quad (16)$$

3. Numerical simulation

3.1. Evaluation methods of energy absorption

Acting as a novel energy absorber, the energy absorption capacity of the spiral TW tube is the most important property that should be paid attention to. There are several indicators to evaluate this capacity, e.g. total absorbed energy during crushing process (W_{total}), absorbed energy per unit mass (W_m) and average crash force (F_{avg}).

As the key indicator used for assessing the capacity of absorbing impact energy, the total absorbed energy (W_{total}) can be determined mathematically as

$$W_{total} = \int_0^{\delta} F(\delta) d\delta \quad (17)$$

where δ is the crushing displacement and $F(\delta)$ is the instantaneous crashing force with a function of the displacement δ .

The absorbed energy per unit mass (W_m), which is also called specific energy absorption (SEA) in some literatures [11], can be worked out by

$$W_m = \frac{W_{total}}{m} = \frac{\int_0^{\delta} F(\delta) d\delta}{m} \quad (18)$$

where, m is the total mass of the spiral TW tube. Since the total length of the sheet metal used for manufacturing the spiral TW tube L can be obtained by Eq. (11) or (12), the total mass m can be worked out if the material density and the height of the spiral TW tube are given.

The average crashing force (F_{avg}) is also one of the parameters to assess the energy absorption capacity of a structure, which can be calculated by W_{total} divided by the crushing displacement δ as

$$F_{avg} = \frac{W_{total}}{\delta} = \frac{\int_0^{\delta} F(\delta) d\delta}{\delta} \quad (19)$$

3.2. Finite element modeling

In this work, the crashworthiness and the energy absorption characteristics of the spiral TW tubes undergoing impact loading were investigated by means of numerical simulations. Those numerical simulations were carried out by using commercial explicit finite element code LS-DYNA.

For simulating impact loading situation, two rigid planes were applied to crush specimen (i.e. the spiral TW tube). One rigid plane was stationary fixed at the bottom for supporting the specimen, while another one moved toward the specimen with a certain impact speed from the top of the specimen. A typical finite element meshed model is shown in Fig. 6 where the moving rigid plane is concealed for better illustration.

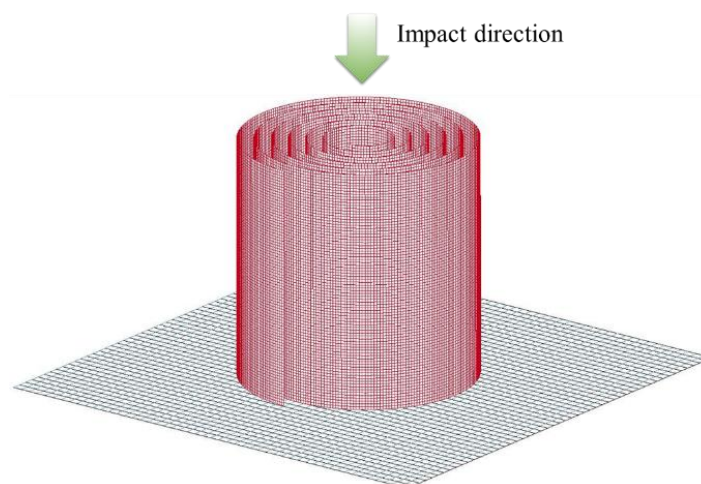


Figure 6. A typical finite element meshed model for spiral thin-walled tubes.

In this work, the selection of the specimen materials referenced that of the literature [6], namely aluminum extrusion AA6061 T4, with Young's modulus $E = 70$ GPa, Poisson's ratio $\nu = 0.28$, yield strength $\sigma_y = 110.3$ MPa and ultimate strength $\sigma_u = 213$ MPa. Likewise, the tensile stress-strain curve and power law expression were also the same as that of the literature [6].

3.3. Results and discussions

At first, collapsing deformation of the spiral TW tube during impacting process is discussed. Let's take the case shown in Fig. 7 for example, where a specimen was simulated to be crushed by the moving rigid plane with an impact speed 10 mm/s. The specimen was obtained by rolling the sheet metal round the mold of which the diameter is 20 mm (i.e. $d_M = 20$) with 6 turns (i.e. $n = 6$), and the sheet metal end was free (as shown in Fig. 2 (c)). The thickness of the sheet metal for manufacturing the specimen was 0.2 mm (i.e. $t = 0.2$ mm) and the height of the specimen was 100 mm.

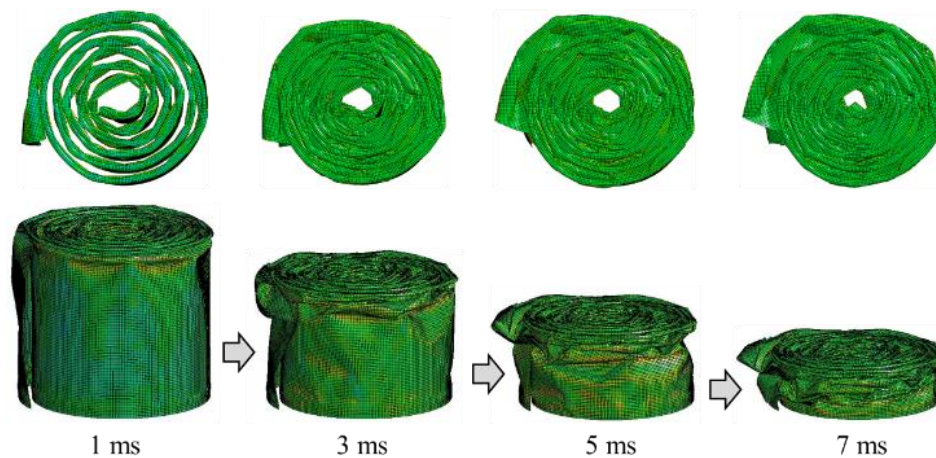


Figure 7. Collapsing deformation process of the spiral thin-walled tube ($d_M = 20$, $n = 6$).

The whole collapsing deformation process of this specimen is shown in Fig. 7. It can be seen that the sheet metal of every turn incrementally collapsed in the manner of so called diamond collapse mode, which means that the collapsing deformation mode of some spiral TW tubes during impacting process is similar to that of some TW circular aluminum tubes with certain sizes [2, 3].

Besides the above case, more simulation analyses were carried out in order to investigate the influence of the turn number (n) and the mold diameter (d_M) on the energy absorption performance of the spiral TW tubes. The cases with the turn numbers (n) in the range of 2 to 10 and the mold diameters (d_M) in the range of 0 to 60 were compared. For the sake of comparative analysis, the heights of the specimens were all selected as 100 mm and the thicknesses of the sheet metal using for manufacturing specimens were 0.2 mm (i.e. $t = 0.2$ mm) uniformly.

The simulation results are shown in Fig. 8 and Fig. 9. It can be found that the force-deformation curves of the specimens are rather similar to those of the most of cellular materials such as honeycomb [20], metal foams [21] and some periodic cellular metals [22-25]. Concretely speaking, at the impacting moment the crashing force of every specimen rapidly increased to the first peak point, but after that the crashing force decreased and then vibrated a little around an approximate constant value with the collapsing deformation until reaching densification stage. Obviously, the most impact energy will be absorbed in the stage that the crashing force slightly fluctuates around the constant value with the collapsing deformation. The absorbed energy can be evaluated by Eq. (17) and Eq. (18). Specifically, the Eq. (17) can be calculated by the method of trapezoid rule of NewtonCotes formula, which can refer to the literatures [24, 25]. Likewise, the constant value that the crashing force vibrates around is approximately equal to the average crashing force (F_{avg}) which can be calculated by Eq. (19).

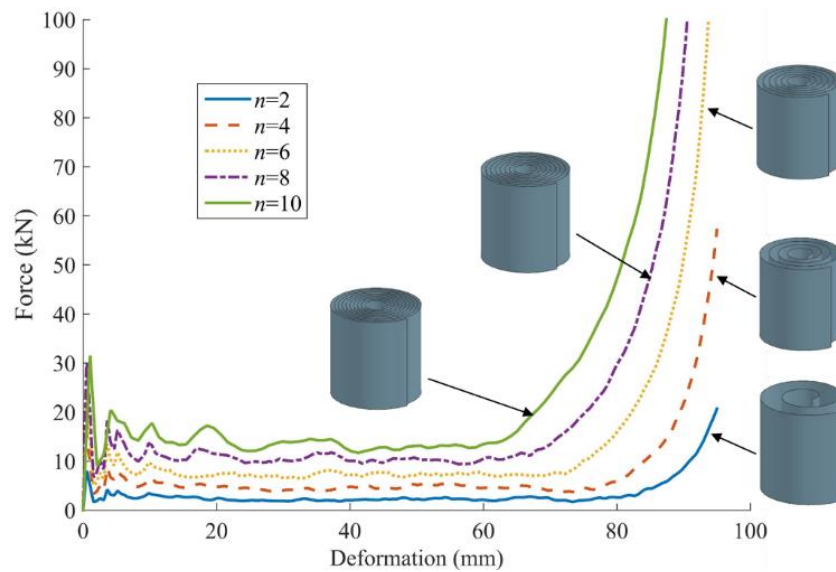


Figure 8. Force-deformation curves of spiral thin-walled tubes obtained by the mold of $d_M = 20$.

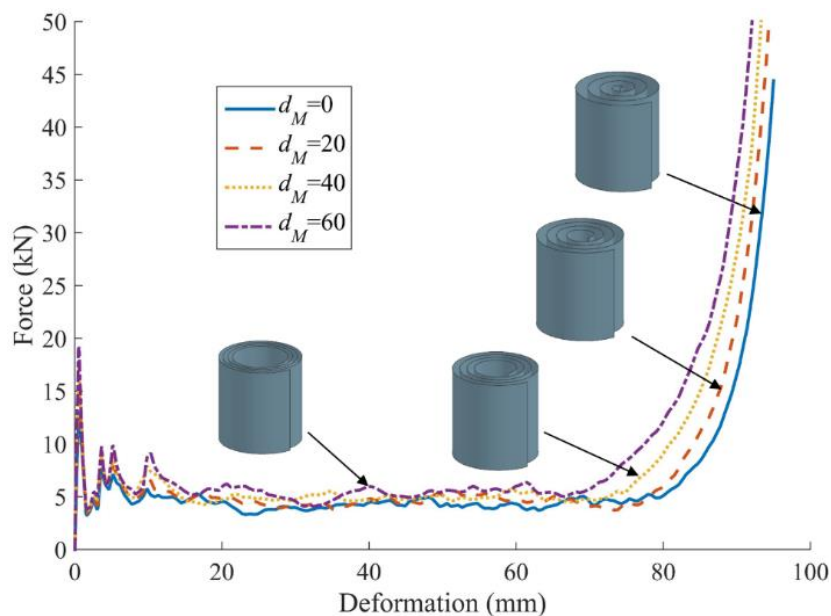


Figure 9. Force-deformation curves of spiral thin-walled tubes ($n = 4$).

From the simulation results shown in Fig. 8 and Fig. 9, it can be found that the spiral TW tube presented in this work indeed has the same energy absorbing performance as other superior cushioning materials such as honeycomb, metal foams and some periodic cellular metals. That is to say, the spiral TW tubes are very suitable for energy absorption and have a great potential used in passive safety area.

4. Conclusion

As a novel and promising structural component used for energy absorption, the spiral TW tube was investigated in this work, concerning its manufacturing process, geometry structure, dynamic crushing and energy absorbing performance under impact loading. The conclusions can be drawn as follows:

Firstly, the spiral TW tube can be easily fabricated by sheet metal rolling, meanwhile, the production cost is rather low because the manufacturing process can be carried out by just one cylindrical bar serving as the mold.

Secondly, the geometry structure of the spiral TW tube was studied by formulation method. The approximate equation for calculating the required length of the sheet metal used for manufacturing the spiral TW tube was derived. Furthermore, if springback occur, the value of the gap among the spiral wall after springback can be worked out by the calculation method given in this work.

Finally, the dynamic crushing and energy absorbing performance of the spiral TW tubes were investigated by means of simulation analysis. The analysis results show that the spiral TW tube has a similar energy absorbing performance as other superior cushioning and energy absorbing materials, so that is to say, has a great potential used for passive safety area.

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