

A new local thickening reverse spiral origami thin-wall construction for improving of energy absorption

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Abstract. As an effective and representative origami structure, reverse spiral origami structure can be capable to effectively take up energy in a crash test. The origami structure has origami creases thus this can guide the deformation of structure and avoid of Euler buckling. Even so the origami creases also weaken the support force and this may cut the absorption of crash energy. In order to increase the supporting capacity of the reverse spiral origami structure, we projected a new local thickening reverse spiral origami thin-wall construction. The reverse spiral origami thin-wall structure with thickening areas distributed along the longitudinal origami crease has a higher energy absorption capacity than the ordinary reverse spiral origami thin-wall structure.

1. Introduction

In the recent years, in order to realize the sustainable development strategy, especially in the field of energy conservation and environment protection, many lightweight and safety structures have been proposed.

Side members are the primary energy-absorbing components that are set up in the front right and left sides of a vehicle. To ensure adequate survival space for passengers in the case of a vehicle crash, the deformation length of the front side members is required to be long enough and the energy absorption should be as much as possible. Crash energy absorption is always accompanied by Euler buckling, and once the structure bends to one side, it can no longer absorb energy. Hagiwara^[1] (1991) worked out the buckling wavelength of a side member: the structure underwent an accordion crease during the vehicle crash process but the deformation length was only set to 70%. Nojima^[2] (2002) first defined the concept of origami engineering and proposed many origami structures. Zhong^[3] (2014) introduced folded structures constructed from flat materials, thereby broadening and enhancing the origami theory. Hagiwara et al. ^[4,5] (2003, 2004), proposed the most representative tubular origami structure named reverse spiral origami thin-wall structure that is able to achieve a deformation length of 90%. Zhao^[6] (2010) utilized optimization technology on the reverse spiral origami structure. The literature profiled indicates that energy absorption of this structure is about 1.91 times that of the collapsed structure of a traditional rectangular section, and 1.37 times that of an uncollapsed traditional rectangular section of the same mass.

Although the structure receives a full performance in deforming process, because of the origami creases, the support force along the longitudinal direction is decreased. In order to increase the support strength of the reverse spiral origami structure, we proposed a new local thickening reverse spiral origami thin-wall structure for better energy absorption.



2. Reverse spiral origami thin-wall structure

Figure.1 shows the side member of the vehicle. In order to design high energy absorption and avoiding of Euler buckling side member, the reverse spiral origami thin-wall tube is proposed. As is shown in Figure.2, a reverse spiral origami structure is designed from a twisted polygon section pipe with a vertical cylindrical shell along the axial direction. When there is an impact load on the end surface of the structure, crash deformation can be guided by the folding edges. Because of its energy absorption character, the structure is applied to the side member of the vehicle.

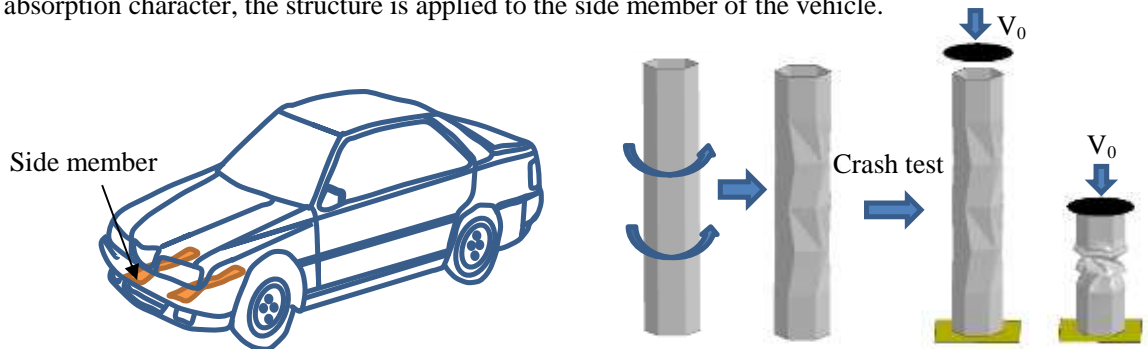


Figure.1 Side member of the vehicle

Figure.2 Reverse spiral origami thin-wall structure

In the deformation process, many wrinkles are generalized and folded like a spring, which can effectively avoid collapse in the transverse direction. However, the origami creases also weaken the support force of origami structure and decrease its energy absorption.

3. Reverse spiral origami thin-wall structure of local strengthening

When the reverse spiral origami structure is processed by hydroforming, the thickness distribution can be effected by the original diameter of pipe. In the hydroforming process, the separated mould moved to form a sealed space, then the liquid is loaded inside the tube and the tube deformed to be the shape of mould.

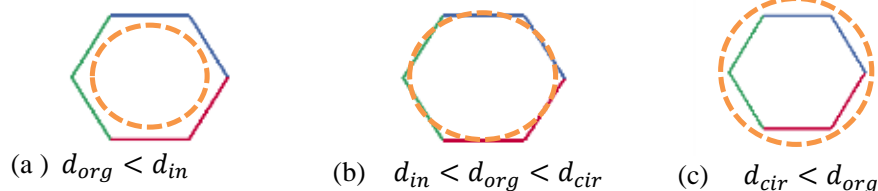


Figure.3 Relationship of pipe and mould (d_{org} is diameter of pipe, d_{in} is inscribed diameter of mould, d_{cir} is circumradius of mould)

As is shown in Figure.3, when $d_{org} < d_{in}$, before hydroforming, the pipe doesn't contact with mould. When the hydraulic pressure is loaded inside the pipe, because of the tension force, the pipe is becoming thinning in the whole hydroforming process. And the pipe may fracture at last. When $d_{in} < d_{org} < d_{cir}$, before hydroforming, the pipe contact with mould, thickness of longitudinal creases area of the pipe is thickening while thickness of transverse and diagonal creases area of the pipe is thinning. Under this condition, the thickness distribution of pipe is easily controlled. When $d_{cir} < d_{org}$, the material is accumulated along the longitudinal direction, the pipe may wrinkle at last.

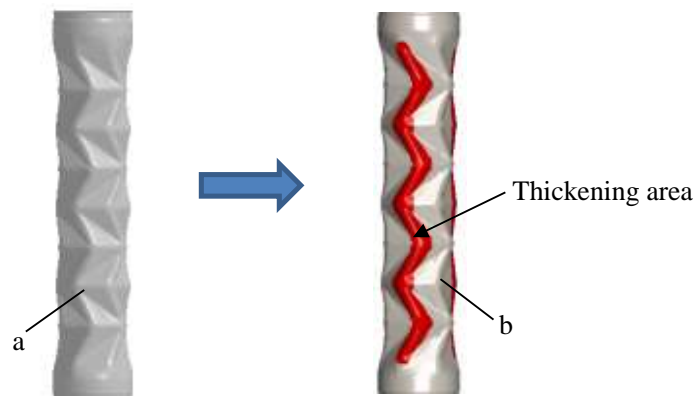


Figure.4 A local strengthening reverse spiral origami structure

When $d_{in} < d_{org} < d_{cir}$, it is easy to adjust the thickness distribution without rupture and wrinkle. In order to enhance the support force along the longitudinal direction, we designed a local strengthening reverse spiral origami structure as shown in Figure.4. The area along longitudinal direction of the tube is thickened and the support force is enhanced and the enhanced structure can absorb more energy than ordinary reverse spiral origami structure.

4. Reverse spiral origami thin-wall structure of local strengthening

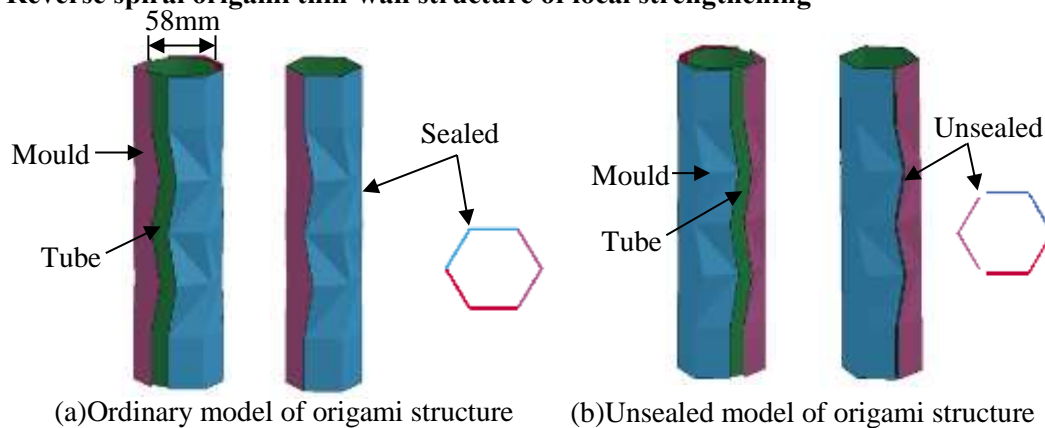


Figure.5 Simulation model of hydroforming

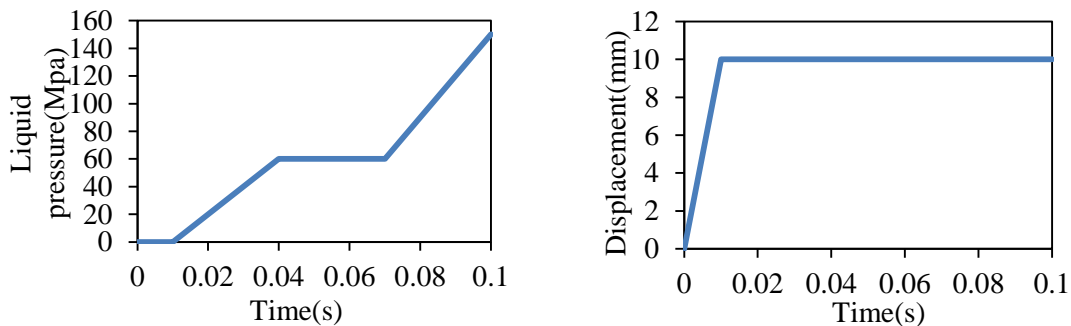


Figure.6 Loading curve of hydraulic pressure and displacement of mould

In order to research the energy absorption character of local strengthening reverse spiral origami structure, we made use of unsealed mould for hydroforming. The width of separated mould is 3mm smaller than the ordinary mould, and after the separated moulds assembly a whole mould, there is 6mm space left between the separated moulds as shown in Figure.5. A 3D model of a reverse spiral origami structure was built and the deforming process was calculated by Ls-Dyna software. The pipe has a length of 270 mm, diameter of 58 mm, thickness of 1 mm, torsion angle of 15°, and segment length of 45 mm. The element sizes for the die, punch, and tube were 1 mm. The moulds are assumed to be rigid bodies. Figure.6 shows the loading curve of hydraulic pressure and displacement of mould.

5. Simulation results and discussion

The Figure.7 showed the thickness distribution of reverse spiral origami structure. The maximum thickness of structure processed by ordinary sealed mould and unsealed mould is 1.201mm and 1.211mm. The minimum thickness of origami structure is reduced from 0.977mm to 0.968mm. The thickness difference has been improved by 8.48%.

In order to research the energy absorption character of designing origami structure, the simulation of crash test as is shown in Figure.8 has been carried out. The simulation model includes the model of origami structure processed by ordinary sealed mould, unsealed and the model with mean distribution of 1.028mm.

Figure.9 shows the absorption energy in the crash test. The absorption energy of origami structure processed by unsealed mould is greater than the structure processed by ordinary sealed mould. The energy absorption of origami structure by sealed and unsealed mould is 33.3% and 43.8% more than an origami structure with mean thickness.

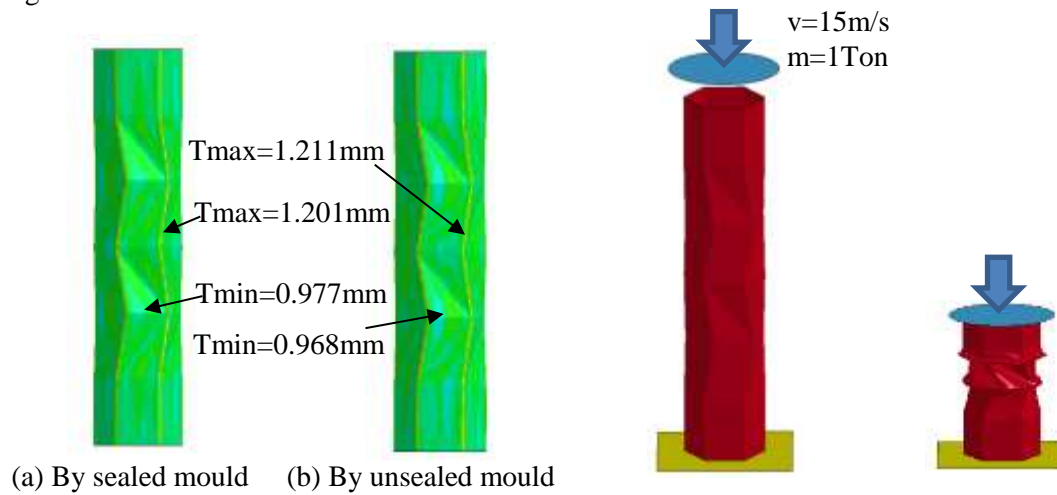


Figure.7 Thickness distribution after hydroforming

Figure.8 Crash test model

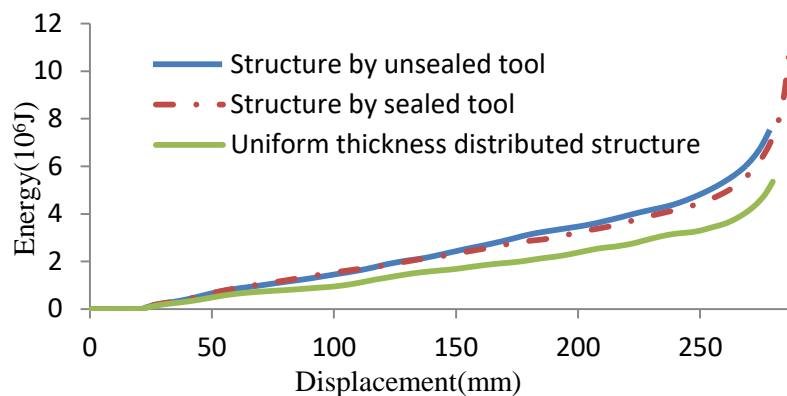


Figure.9 Crash model different reverse spiral origami

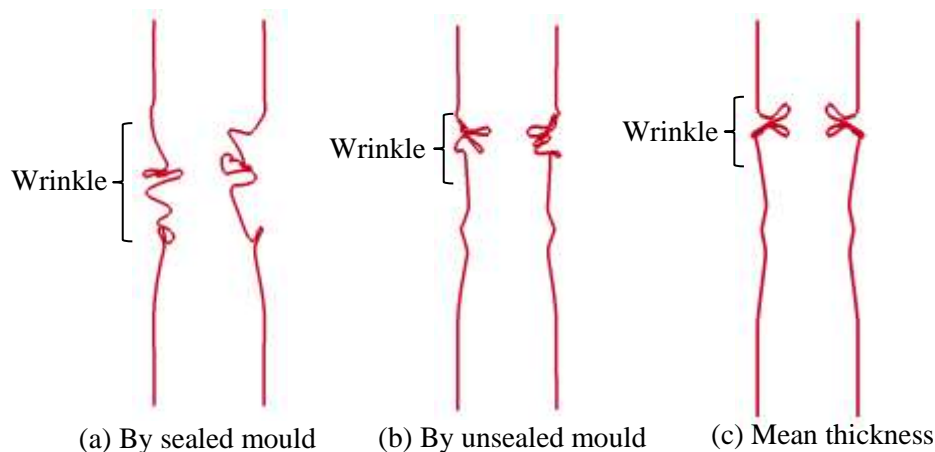


Figure.10 longitudinal section of different origami structure in crash test

Figure.10 shows the longitudinal section of the different origami structures in crash test. The origami structure processed by ordinary and unsealed mould has more wrinkle than the structure with mean thickness distribution. Thus, these origami structures can absorb more energy than the structure with mean thickness distribution. But because the wrinkles density of origami structure processed by sealed mould is sparser than the wrinkles density of origami structure processed by unsealed mould, the structure processed by sealed mould absorb less energy than the structure processed by unsealed mould in crash test.

6. Conclusion

In this paper, we simulated the hydroforming process of reverse spiral origami structure and discussed the formability and energy absorption ability. On the base of thickness distribution, we proposed a local strengthening reverse spiral origami structure and compared the energy absorption of origami structure processed by ordinary mould and unsealed mould. The conclusions are written as follows.

- (1) The thickness distribution of reverse spiral origami structure has a relationship with the diameter of original tubes. When the diameter of pipe is smaller than inscribed diameter of mould, the pipe may be rupture in hydroforming process. When the diameter of pipe is bigger than circumradius of mould, there may be wrinkle in the hydroforming process. When the diameter of pipe is bigger than inscribed diameter of mould and smaller than circumradius of mould, thickness of structure can be adjustable without rupture and wrinkle.
- (2) The local strengthening reverse spiral origami structure processed by unsealed mould has a thicker thickness distribution along the longitudinal origami crease. This kind of thickness distribution can improve support force of origami structure. The energy absorption of this structure is 43.8% more than origami structure with mean thickness and 7.87% more than origami structure processed by ordinary sealed mould.
- (3) The local strengthening reverse spiral origami structure has a relationship to the diameter of pipe and the space of separated mould. It is necessary to discuss their relationships and get the best design of this structure.

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