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Deformation Mode and Energy Absorption Analysis of Bi-Tubular Corrugated Crash Box Structure

Ismi Choirotin[1,2*], Moch. Agus Choiron[3], Anindito Purnowidodo[3], Djarot Bangun Darmadi[3]

[1]Doctoral Student of Mechanical Engineering Department,
University of Brawijaya, MT Haryono 167, Malang, 65145, INDONESIA

[2]Mechanical Engineering Department,
University of Islam Malang MT Haryono 193, Malang, 65145, INDONESIA

[3]Mechanical Engineering Department,
University of Brawijaya MT Haryono 167, Malang, 65145, INDONESIA

*Corresponding author

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Abstract: In this research, the characteristic of crash box with bi-tubular corrugated structure are numerically examined under axial loading condition. The crash box characteristic were observed in the compression test of aluminum alloy (AA6061) using ANSYS software. The comparation were carried out on two geometrical types, namely: ordinary corrugated tube (OCT) and bi-tubular corrugated tube (BCT). The result showed that comparing both of crash box structure exhibit the Simultaneous crush mode (S-mode) deformation. The force-displacement present a stable diagram without any fluctuation. BCT structure resulted 71% energy absorption capacity increment compared to OCT structure. The highest energy absorbed by BCT structure was 10.8 kJ. There are no significant specific energy absorption different between the specimen and the highest SEA occur at OCT structure with 31.281 kJ kg^{-1}.

Keywords: Crash box, corrugated, bi-tubular, axial loading, energy absorption

1. Introduction

Safety reason was an important consideration in designing a vehicle. One of the passive safety systems used to protect passengers is crash box. Crash box is a thin-walled tube that aims to reduce the collision risk on passengers by absorbing the impact energy and transform it into plastic deformation [1]. This thin-walled tube is widely used as a safety system because of its low-cost, denote high strength, high rigidity, and excellent characteristics in absorbing energy [2], [3]. The Energy absorption during a collision switch over a uniform folding in the tube structure. A uniform folds that occur in the tube structure, exhibit it's absorbs collision energy properly. A passive safety structure said have a good performance if it can absorb large amounts of collision energy without any buckling. Nowadays many studies develop to improve the energy absorption characteristics of crash boxes. Various design schemes have carried out include the influence of cross-sectional shapes on a single tube, multi-cell design, the type of material used, giving the trigger shape for the folding initiation and other types of designs. Experimental and numerical investigation of several different cross sections tube types (circular, square, rectangular, pyramidal and conical) were studied [4], [5], [6]. All type of tubes with similar volume, height, average section area, thickness and material are subjected under axial quasi static loading. The investigation proven that the geometry of the tubes are greatly determine the structures ability to absorb energy. Other studies have concluded that circular tubes have the best ability to absorb energy, when compared

*Corresponding author: ismi.choirotin@unisma.ac.id
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to the other tubes [7]. The weakness of this single tube structure is a high initial peak crushing force (IPCF), that make it has a big risk of buckling [3].

Corrugated tube is designed to overcome and reduce a high initial peak crushing force problem. This corrugated tube can reduce the IPCF, because it has an initial shape which make it deform easily following the existing corrugation pattern. Previous research studied the effect of corrugation to the crushing behaviors of circular aluminum tube experimentally. A simple tube and sinusoidal corrugation tube characteristic were compared under axial loading. The result showed that the use of tubes with corrugated surfaces make the deformation process predictable and controlled [8]. Despite of corrugated tube can reduce the initial peak crushing force, the total energy absorption value is lower than single tube performance. Another study conducted to compare the behavior of a single tube with a double tube (bi-tubular) under quasi-static compressive loading [9]. A stainless steel bi-tubular were consist of an outer circular cylinder and inner tube with different cross section area types (triangle, square and hexagon). From these experimental studies it was found that a double tube absorbing more energy if compared to a single tube. The efficiency of energy absorption on bi-tubular structure was increased when compared to single tube structure. Through many studies have been done in this area, this research will focused study the deformation mode and the energy absorption characteristics of the crash box using a double tube (bi-tubular) and corrugated surface under axial loading. In this study, a computer simulation method used to analyze the deformation mode and energy absorption of bi-tubular corrugated crash box.

2. Method and Materials

This study proposes bi-tubular corrugated tube (BCT) structures in order to offer better energy absorption in comparison with ordinary corrugated tube (OCT). It is interesting to note that bi-tubular corrugated structure are design as double cell tube, which the second tube (smaller diameter) placed inside the first one. In all cases, tubes have 150 mm length and 1.8 mm thickness. The geometry of corrugated tube was assume to be sinusoidal with wavelength (W) = 6.26 mm, and amplitude (A) = 1 mm. The main corrugated tube have 70 mm diameter (D1) for both of OCT and BCT structure, whereas BCT crash box structure have the second tube with 50 mm diameter (D2). The geometry of single corrugated tube and bi-tubular corrugated tube structure are shown in Fig. 1.

The current numerical investigation is performed using ANSYS workbench 18.1. The finite element modelled as three main parts as illustrated in Fig. 2. The three main parts are (1) the corrugated tube (specimen), (2) Impactor and (3) Lower Die. The aluminum AA 6061 T4 is applied as corrugated tube materials. All corrugated tube was modelled as bilinear isotropic hardening material. The mechanical properties of AA 6061 T4 are as follows: density (ρ) is 2790 kg m-3, Young's modulus (E) is 70 GPa, Poisson's ratio (ν) is 0.28, Yield strength (σ_y) is 145 MPa and tangent modulus is 450 MPa. The corrugated tube was discretized using 1 mm quadrilateral elements and placed among lower die and Impactor. The Impactor and lower die are modelled as rigid bodies to ensure that they did not deform during loading process. The corrugated tube is loaded by the impactor which mass is considered 103 kg. The Impactor allowed to move in the y-axis direction only with the velocity of 10 mm s-1. To reduce the computation time of numerical simulation, a mesh size of 3 mm is selected for rigid body. The von misses criterion was used to define failure conditions, by determine stress as an equivalent (von misses) stress in the solution step.

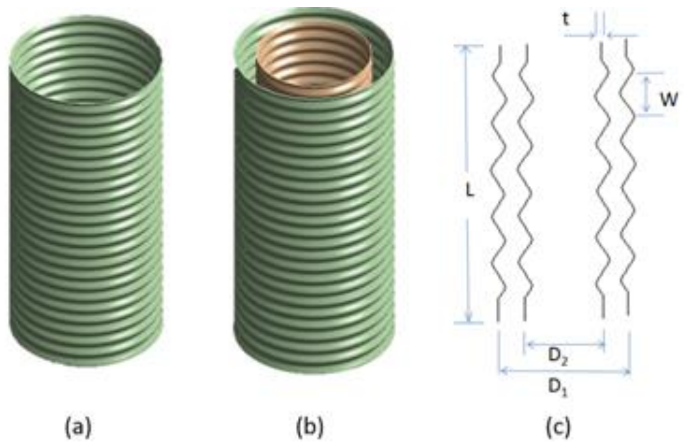

Fig 1 - The geometry of corrugated tube: (a) Ordinary corrugated tube; (b) Bi-tubular Corrugated Tube; (c) corrugated tube dimension

The validation of this study was done by previous research [10], by comparing finite element modeling to experimental compression test of the ordinary corrugated tube (OCT). The OCT specimen has 70 mm diameter, 80 mm length and 2 mm thickness loaded by an instiron 8502 hydraulic testing machine (250 kN). The OCT's corrugation profile is as follows: wavelength (W) = 10 mm and amplitude (A) = 2 mm. The validation resulted in a good agreement deformation mode, as shown in figure 3. The force – displacement performance error rate between the experiment and the finite element model is less than 5%. Accordingly, the finite element model has acceptable accuracy and can be used for the further study of BCT's crash box structure.

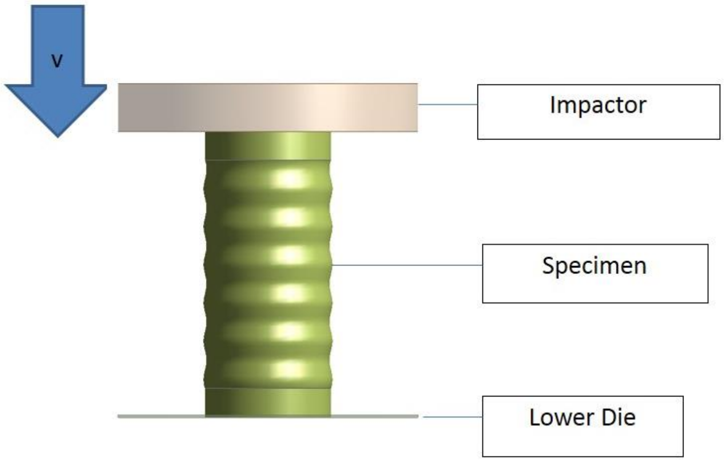

Fig. 2 - Finite element modelling of crash box compression test

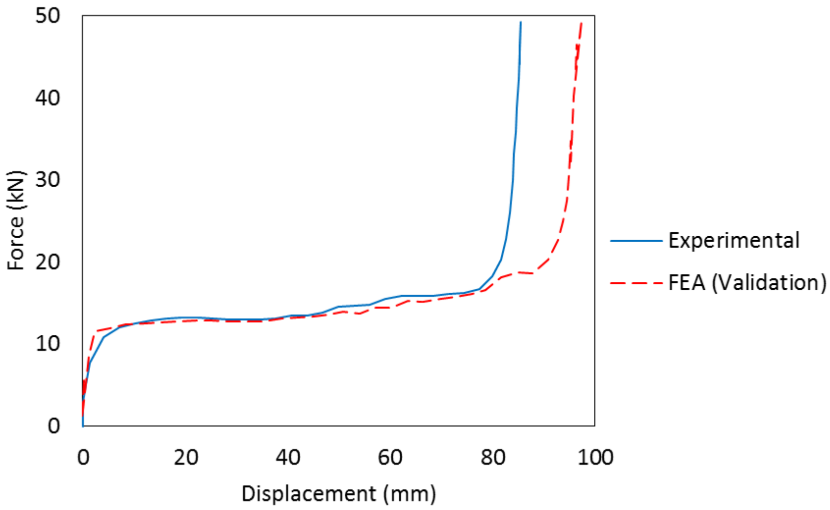

Fig. 3 - Force-displacement diagram

3. Result and Discussion

The behavior of crash box under axial compression was called deformation mode. The tube deformation mode during loading depends on its material characteristic, loading velocity, and geometric structure. The corrugated tube deformation mode is classified as axisymmetric modes and asymmetric modes. The axisymmetric modes deformation was further classified into the Progressive crush mode (P-mode) and the Simultaneous crush mode (S-mode) [11]. Those deformation modes are classified base on the folds that generate the deformation or crushing region at random times. The load-displacement curve difference between P-mode and S-mode are showed in figure 4. Fig. 5 exhibits the deformation of crash box structure for each displacement, where (a) shows the deformation of OCT structure. Refer to the result during compression loading, all folds on corrugated tube wave was fold at the same times. The corrugated tube design have 24 sinusoidal patterns, and each pattern fold simultaneously. This type of deformation pattern is known as the Simultaneous crush mode (S-mode). The similar phenomena take place on BCT structure as shown in Figure 3b. Main corrugated tube fold behavior similarly to the OCT structure due to their identical geometry. The second corrugated tube or later we call it as inner tube also demonstrate the S-mode deformation, wherein the crushing region has the shape of fold appear at the same time on each sinusoidal wave. Detail of the S-mode deformation fold cross section are shown in figure 6, those folding pattern took when the deformation reach 60 mm.

On the other hand, the P-mode deformation is come about crushing region begins to appear at the loading side, whereas the reverse side remains static. The initial fold occurs at the top of corrugated tube until it was fully compressed. Passingly the second fold appears at the second corrugation pattern when the stress of the first fold reaches the maximum value. As mention before, the type of deformation mode is closely related to the material characteristic, loading velocity, and the geometry of the structure. The deformation mode varies at different radius-thickness ratios

(D/2t) of the tube [2],[10]. Tube structure with small D/2t brings about S-mode deformation. In this numerical study, the OCT structure with D/2t of 19.4 which is categorized into a small D/2t value exhibit the S-mode deformation. Likewise in the BCT deformation mode, the inner tube with D/2t of 13.8 is also classified as a small D/2t value. The BCT structure indicates the deformation mode as the S-mode deformation. Refer to the earlier research [2] the increment of radius-thickness ratio will reduce the absorbed energy, as the S-mode deformation denote higher energy absorption by the crash box structure.

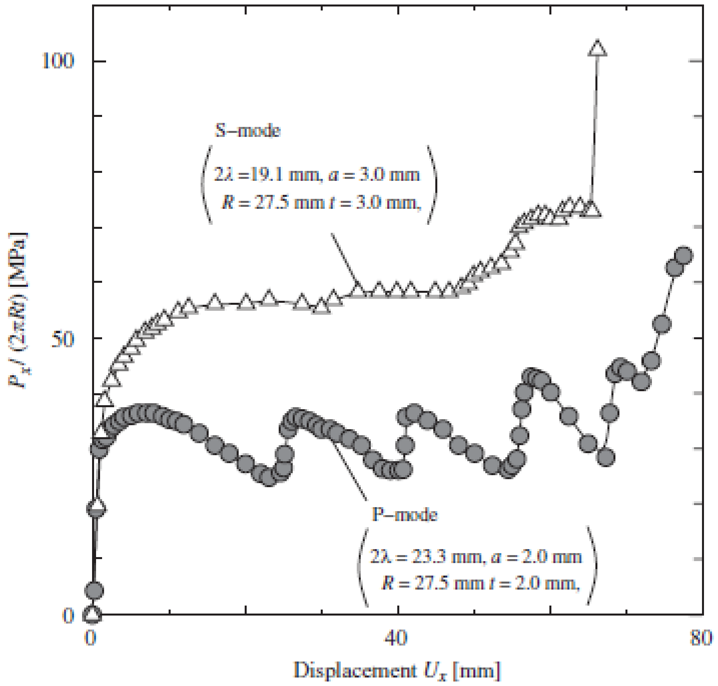

Fig.4 - Experimental result of Load-displacement curves for A 5052 [11]

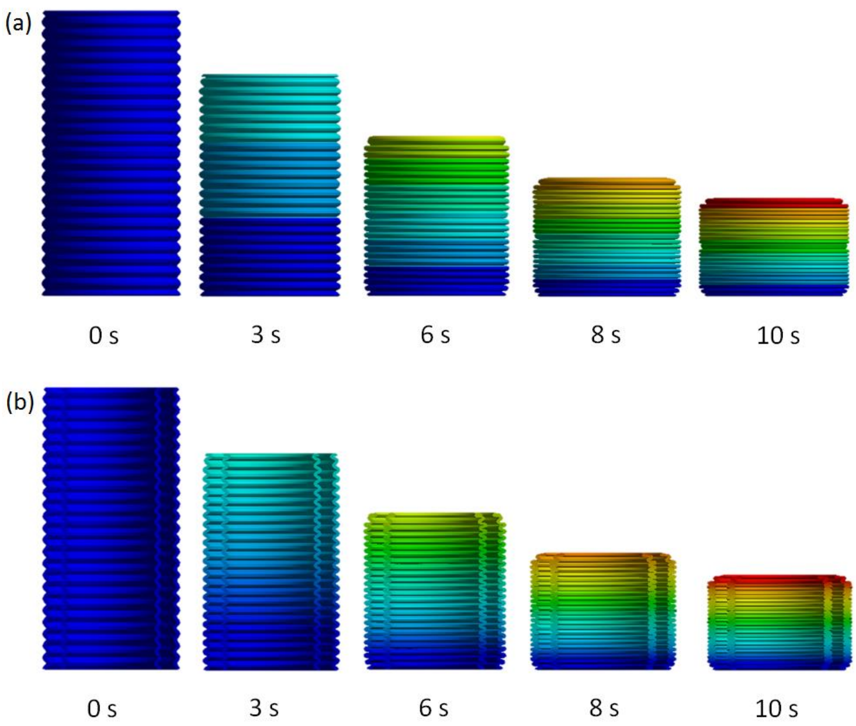

Fig. 5 - Deformation mode of corrugtaed tubes: (a) Ordinary corugated Tube; (b) Bi-tubular corrugated tube

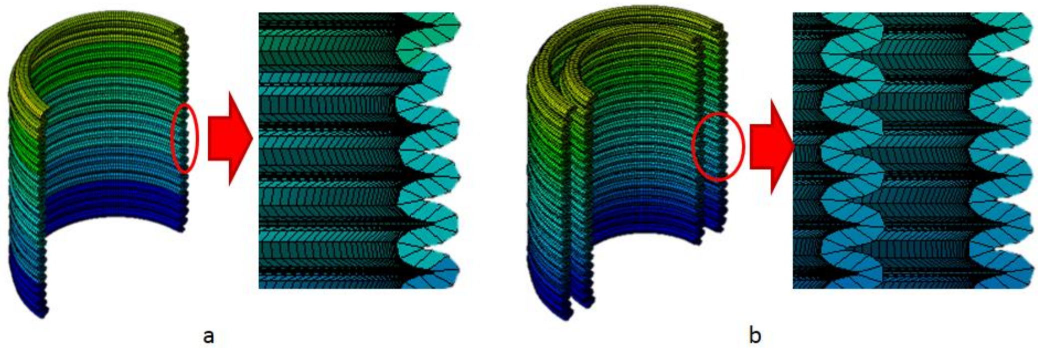

Fig. 6 - The cross section of S-mode deformation, (a) OCT simultaneous fold; (b) BCT simultaneous fold

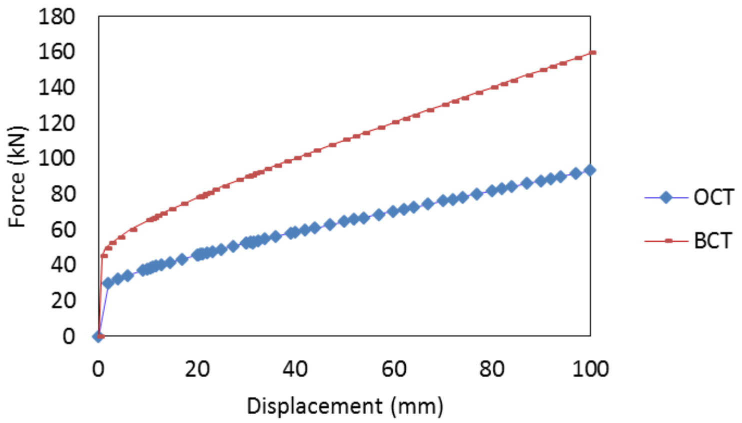

Fig. 7 - Force-Displacement characteristic of corrugated tube compression test

Fig. 7 presents the force-displacement characteristic of OCT and BCT crash box structure. The Corrugated tube was designed to overcome and reduce a high initial peak crushing force problem as mention in the research background. Refer to fig. 7, the force-displacement curve exhibit no Initial Peak Crushing Force (IPCF) in both of OCT and BCT structure. The initial crushing force value is lower than the crushing force during deformation process. Low initial crushing force value will reduce buckling possibility of the crash box structure. The BCT structure shows a larger area below force-displacement curve than OCT structure, which indicates BCT structure energy absorption is higher than OCT. Refer to figure 7, both corrugated tubes perform a stable crushing force. It concluded as a stable crushing force due to the absence of fluctuates force along the deformation process. These force-displacement characteristics also indicate the presence of the S-mode deformation. Refer to the previous study [11], fluctuates force illustrates the P-mode deformation (dynamic asymptotic buckling). On the other hand, a stable force-displacement exhibits the S-mode deformation which is sometimes called dynamic plastic buckling deformation mode.

Tabel 1 -The simulation result data

Structure	***Displacement (mm)***	**Mass (kg)**	**F max (kN)**	**EA (kJ)**	**SEA (kJ kg^{-1})**	**Deformation Mode**
OCT	100	0.201	93,411	6.280	31.281	S-mode
BCT	100	0.344	159.590	10.800	31.230	S-mode

The result data of the corrugated tubes simulation are presented in Table 1. The Ordinary corrugated tube (OCT) is designed as a single tube with a mass of 0.201 kg, while the Bi-tubular Corrugated Tube with a mass of 0.344 kg. Total energy absorption represents the specimen's capacity in absorbing the crushing energy. The simulation result shows that the BCT structure absorbs the highest energy with 10.8 kJ. Total energy absorbed by the OCT structure was 6.28 kJ. The comparison value of energy absorption during deformation between SCT and BCT is depicted in Figure 8. Refer to the results, the absorbed energy increasing as the displacement increment. Total energy absorbed by BCT crash box is higher than OCT, it is caused by volume and mass of BCT are higher than OCT. That reality means, even if BCT crash box structure absorbed more energy, the mass of BCT crash box is heavier than OCT structure. Specific energy absorption (SEA) was the common parameter that compared the energy absorption capacity of crash box structures with different mass. The value of SEA is given by dividing total energy absorption by the mass of the structure. Table 1 shows that OCT structure exhibit 31.281 kJ kg^{-1}, while BCT structure resulted in 31.230 kJ kg^{-1} of specific energy absorption. A comparison of SEA value between OCT and BCT structure demonstrate in figure 9. From that result indicate that there is no significant SEA value different among OCT and BCT crash box structure. From this investigation, we can conclude that with a similar SEA, the energy absorption of BCT crash box structure increased 71%, compared to OCT structure.

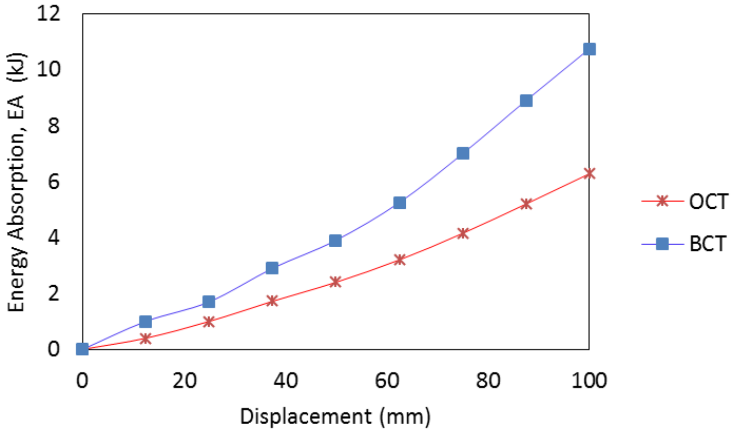

Fig. 8 - Correlation between displacement and energy absorption of OCT and BCT structure

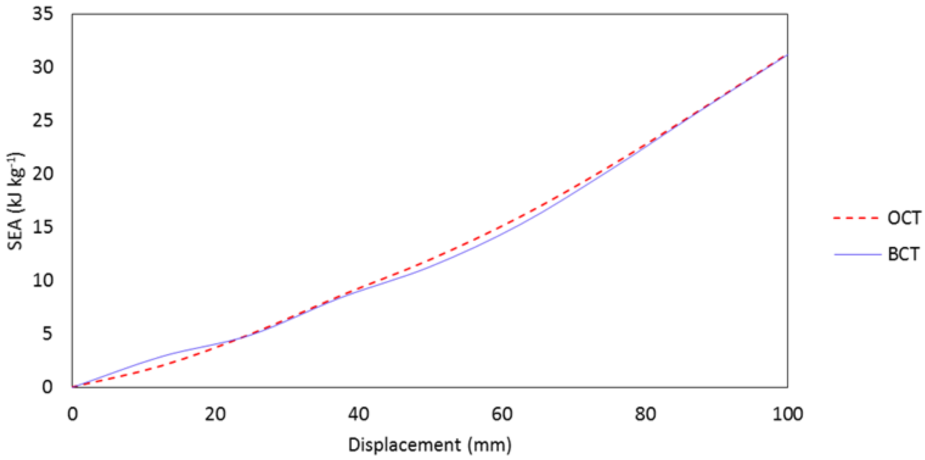

Fig. 9 - SEA comparison between OCT and BCT crash box structure

4. Conclusion

In this study, a comparison between ordinary corrugated tube (OCT) and Bi-tubular corrugated tube (BCT) crash box structure was investigated by computer simulation. The research and analysis conclusion is as follows:

- The deformation mode that occurs at both OCT and BCT crash box structure is the simultaneous crush mode (S-mode).
- The force-displacement diagram presents a stable crushing force which indicates the simultaneous crush mode (S-mode) deformation.
- The energy absorption performance of BCT is higher than OCT crash box structure.
- Even though BCT has a higher performance in absorbing the crushing energy, there is no significant specific energy absorption value between both specimens.

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