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The Effect of Corner Radius of Square Thin-Walled Structures on Crashworthiness Indicators

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ABSTRACTS

Generally, the crash box on automobile vehicles is a thin-walled structure with a square cross-section. The majority of research was carried out for a long time to find the optimum crashworthiness indicator. In this study, numerical simulations and experimental tests are used to investigate the effect of the corner radius of a square cross-section thin-walled structure on crashworthiness indicators. Quasi-static analysis with mild steel material produces the mean force (P_m) error value is less than 3% while varying the corner radius ranging from zero to 1 mm, 2 mm, and 3 mm shows energy absorption (EA) and peak force (P_{max}) decreased.

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INTRODUCTION

One of the safety designs in vehicles is that it relies heavily on crash boxes to absorb kinetic energy in the event of a collision. A crash box is a thin-walled structure with a square cross-section in simple geometry. This structure is lightweight, has high energy absorption capacity, greater crush length values, and a high energy-to-weight ratio. It is therefore regarded as an essential energy absorption structure [1], [2].

Research on thin-walled square cross-sectional structures was initiated over three decades ago, either experimentally [3]–[5], theoretical predictions [6], [7], or numerical simulations [8], [9]. All these studies lead to the evaluation of energy absorption, continuously refined by modifying multi-cell structures [10], as well as the addition of reinforcement at the corner of the square tube [11]. In addition, the crush initiator is also used to find the effectiveness of energy absorption [12]. However, considering the cost efficiency in the manufacturing process and the availability of specimens in the local market, it is still worthwhile to undertake a low-cost modification by optimizing the corner radius.

This study aims to determine the effect of the corner radius of a thin-walled structure with a square cross-section on the indicators of crashworthiness and the shape of the basic collapse mode. The results are expected to help design energy absorption structures of axial impact.

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METHODS

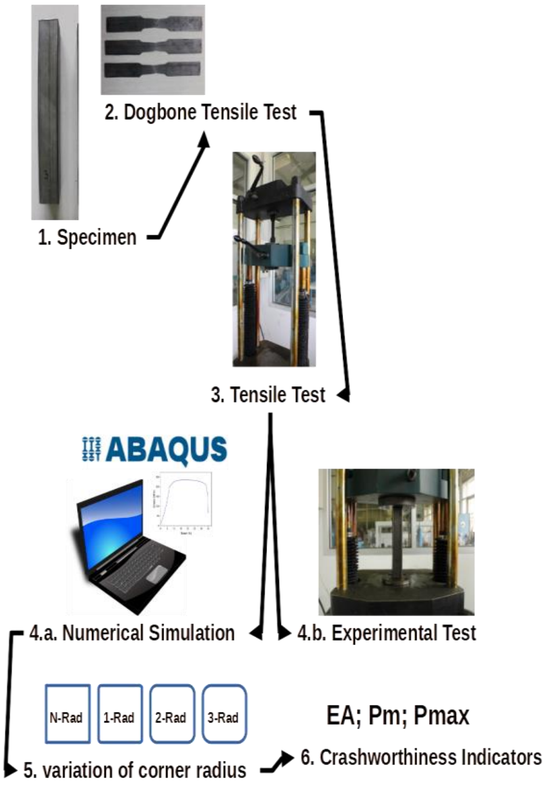


Figure 1. Research Flow Diagram.

A thin-walled structure with a square cross-section was used for this study. A tensile test on specimen pieces was carried out with the ASTM E-8 standard to obtain stress and strain curves. The experimental compression test was carried out in a quasi-static manner as validation of the simulated compression test. The effect of the corner radius on the crashworthiness indicators was predicted by numerical simulation using Abaqus 6.10, as shown in the flow diagram in **Figure 1.**

The geometry of the thin-walled structure with a square cross-section and the numerical simulation setup are shown in **Figure 2.** and **Table 1.** Meshing has been shown to produce convergent data using a size of 2x2 mm [13], [14].

The experimental compression test and numerical simulation took a displacement (d) of 115 mm from a specimen length (L) of 200 mm. The corner radius (R) variation is a square cross-section with no corner radius, a corner radius of 1 mm, a corner radius of 2 mm, and a corner radius of 3 mm represented by N-Rad, 1-Rad, 2-Rad, and 3-Rad, respectively.

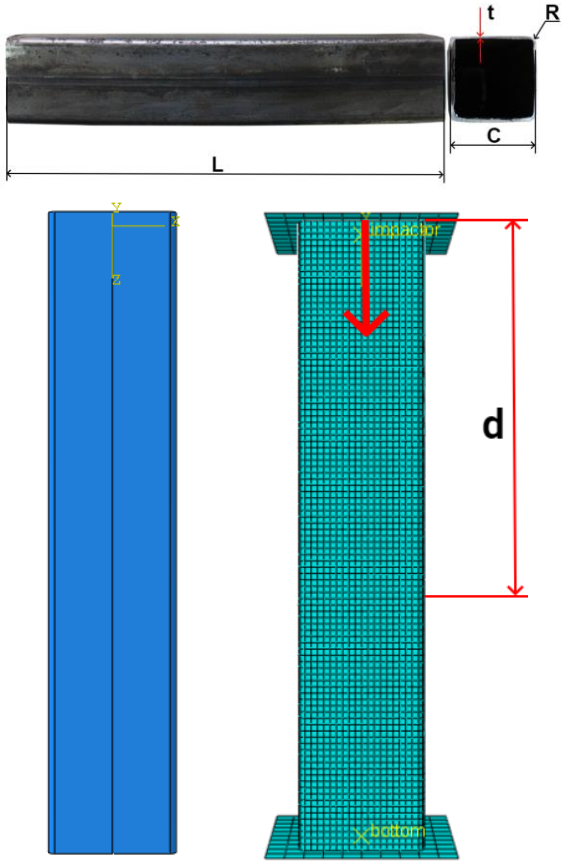


Figure 2. Schematic of Geometry and Numerical Simulation Set Up.

Table 1. Specimen Dimension.

	c (mm)	L (mm)	t (mm)	R (mm)
Dimension	40	200	1	0, 1, 2, 3

The equations for the crashworthiness indicators are obtained from the force-displacement curve described in various references [15], [16].

Energy absorption (EA):

$$EA = \int_{0}^{\delta_{max}} F(\delta)d\delta \quad (1)$$

Where F is instantaneous crushing force, δ is the vertical displacement of impactor mass.

Mean Force (P_m):

$$P_m = \frac{EA}{\delta_{max}} \quad (2)$$

Another equation of the mean force (P_m) for the inextensional collapse mode thin-walled square tube is obtained empirically [4]:

$$P_m = 38.12 \left(\frac{c}{t}\right)^{1/3} M_0 \quad (3)$$

The mean force (P_m) for the extensional generalized mixed collapse mode was improved [17], [18]:

$$P_m = 48.64 \left(\frac{c}{t}\right)^{0.37} M_0 \quad (4)$$

Where c is the length of the side of a square cross-section, t is the wall thickness, and M_0 is a quarter of the mean value of plastic flow stress multiple by thickness squared.

RESULTS AND DISCUSSION

a. Materials and Tensile Test

The thin-walled structure with a square cross-section is a type of mild steel easily found in the Indonesian market. **Figure 3** shows a stress-strain curve resulting from a tensile test with a yield stress value of 200 MPa and maximum stress of 235 MPa. El Reedy [19] said that steel materials based on ASTM standards with yield strengths below 280 MPa could be classified as mild steel.

The tensile test results in engineering stress and engineering strain will be converted to produce true stress and true strain, then used as input for the material in numerical simulations.

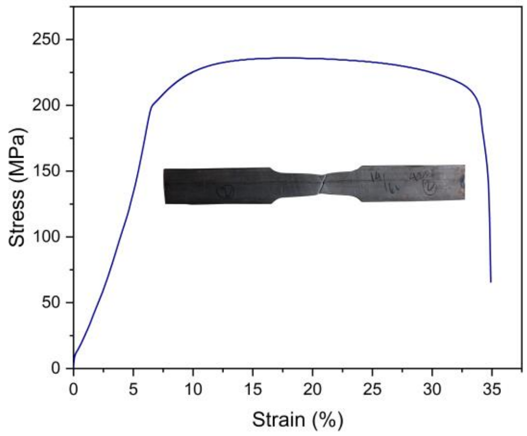


Figure 3. Stress-Strain Curve Tensile Test.

b. Numerical Simulation and Experimental Test Validation

Specimens of thin-walled structures with a square cross-section with a corner radius of 2 mm (2-Rad) were subjected to numerical simulations and quasi-static experimental tests. The final result shows the similarity of shape can be seen in **Figure 4**.

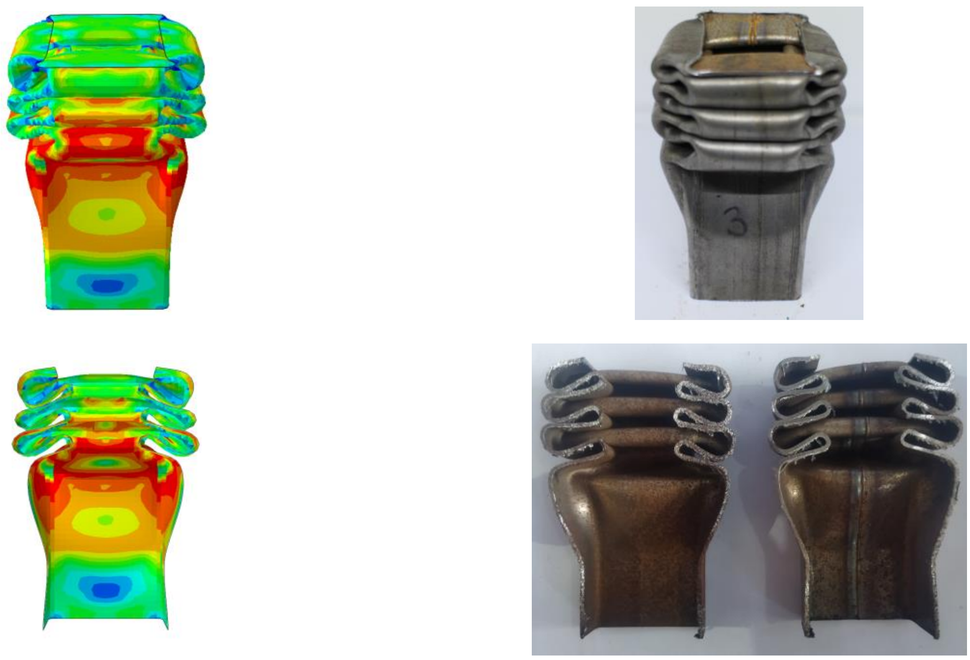


Figure 4. Result of Folding a. Numerical Simulation; b. Quasi-Static Experimental .

The specimen was compressed with a displacement (d) of 115 mm, and six folds were obtained. Ref [4] mentions that the bending form is inextensional basic collapse mode.

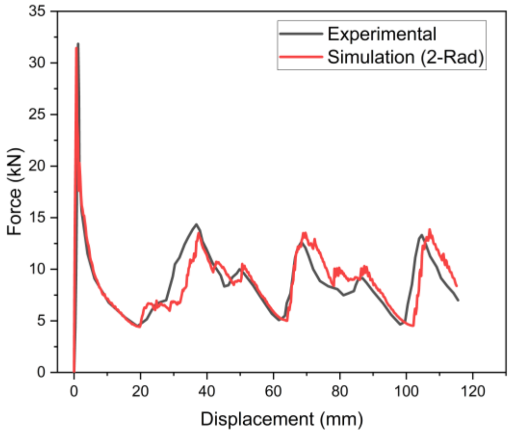


Figure 5. Force-Displacement Curve Validation Experimental and Simulation.

From **Figure 5.** the force and displacement curves are detailed in **Table 2.** The experimental test results and the numerical simulation results are similar in the quantity of the crashworthiness indicators with an error of not more than 5%. Analytically, **equation 3** in Ref [4] of the mean force is 8.93 kN. Compared with the results of the mean force (P_m) of experimental tests and numerical simulations, which are 8.71 kN and 8.87 kN, this value has an error of less than 3%. The results of this validation bring the author's confidence to continue the research by varying the corner radius to find out the effect on the value of the crashworthiness indicators.

Table 2. Crashworthiness Indicators.

	P_{max}	P_m	EA
Experimental	31.85 kN	8.71 kN	1.07 kJ
Simulation	31.45 kN	8.87 kN	1.02 kJ

c. Variation of corner radius of thin-walled structure with a square cross-section.

The variation of the corner radius of the thin-walled structure with a square cross-section is used to determine the changes in the crashworthiness indicators. In addition, the initial observations were on the shape of the basic collapse mode and the folding pattern. In **Figure 6.** the numerical simulation results can be noted that if a thin-walled structure with a square cross-section with a thickness of 1 mm and a length of 200 mm does not have a corner radius or is equal to the thickness value (N-Rad, 1-Rad), it produces an extensional basic collapse mode. Meanwhile, the corner radius is greater than the thickness (2-Rad, 3-Rad), resulting in a consistent inextensional basic collapse mode.

Of the four specimens, the 1-Rad specimen was not fully folded at the ends, where the initial fold (H) was longer than the other specimens. So, if this folding pattern is not maintained, it will turn out to be a global buckling.

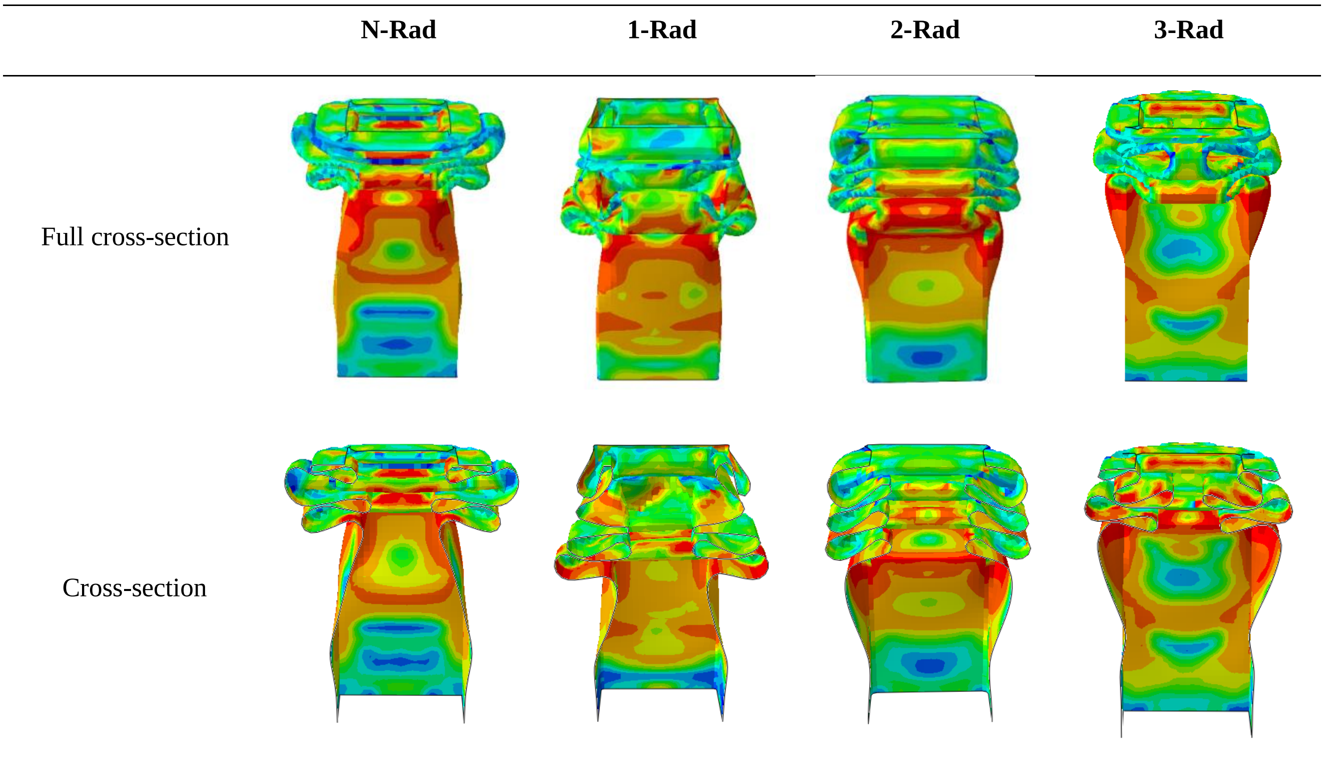
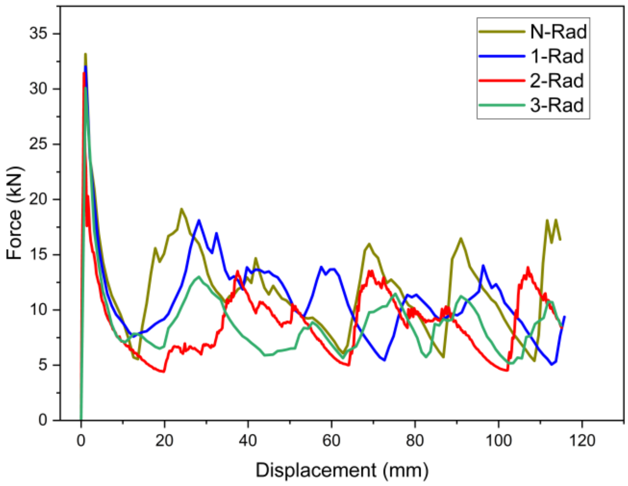
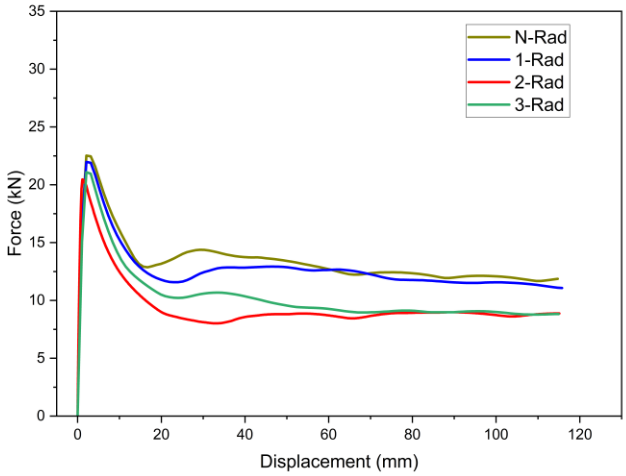


Figure 6. Basic Collapse Mode of Numerical Simulation.



a



b

Figure 7. a. Force-Displacement Curve; **b**. Mean Force-Displacement Curve.

Table 3. Crashworthiness Indicators With Corner Radius .

	P_{max}	P_m	EA
N-Rad	33.17 kN	11.86 kN	1.36 kJ
1-Rad	32.03 kN	11.07 kN	1.28 kJ
2-Rad	31.45 kN	8.87 kN	1.02 kJ
3-Rad	30.09 kN	8.82 kN	1.01 kJ

Further from **Figure 7. a.** The force-displacement curves show the number of folds where the N-Rad, 1-Rad, 2-Rad, and 3-Rad specimens are 5, 7, 6, and 6 folds, respectively. The displacement (d) produces several different folds, except for specimens with an angle radius greater than their thickness.

The mean force (P_m) value also varies with the number of folds. In **Figure 7.b.** and **Table 3.** the highest mean force (P_m) is the N-Rad specimen, which is 11.86 kN, and the lowest is 3-Rad, which is 8.82 kN.

The results of the analytical formula in **equation 4** for the extensional basic failure mode, the mean force (P_m) is 13.38 kN. So for N-rad and 1-Rad specimens, the error with the analytical equation is more than 10%. Meanwhile, for the inextensional basic collapse mode from equation 3, the average force value is 8.93 kN, so the mean force (P_m) of 2-Rad and 3-Rad's errors when compared is ± 3%.

CONCLUSION

A tensile test has been carried out for mild steel type material, which is used as input material properties for numerical simulations. Furthermore, the quasi-static analysis was carried out by compressing the thin-walled structure with a square cross-section which was validated by experimental tests.

The results show good acceptance because the error is less than 3% for inextensional basic collapse mode (2-Rad and 3-Rad). As development in this research, it has answered the goal that it turns out that the corner radius of the square tube influences the crashworthiness indicator, where the more significant the corner radius will reduce P_{max}, P_m, and EA.

To achieve the optimum results of the crashworthiness indicator, the EA should be as significant as possible and the P_{max} as small as possible. It is still open for further research to determine the optimum crashworthiness indicators with various variations and modifications of its geometry.

Author Contributions

The authors contributed equally to this work with concepts, designing the model and the computational and experimental test, and analyzing the data. All authors contributed to the final version of the manuscript.

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