An increase in crashworthiness capability using pyramid arrangement of the crush initiator

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Abstract. Collisions on vehicles could cause injury to passengers such as being thrown from a passenger room. To prevent this, a vehicle structure was not too strong which called by crashworthiness criteria through maximum impact force. This study was conducted to determine the smallest structural strength through maximum impact force in a square column with 0.8 mm in thickness. The column was given holes with 3 mm in diameter as crush initiators. The hole was arranged in pyramid pattern with different level and begun with 1 hole in the square column. The research used the quasi-static concept experimentally with 30 mm/min in movement speed of actuator. The machine used Universal Testing Machine (UTM) with 200 kN in capacities. The result showed that the pyramid arrangement with the highest level had the greatest maximum impact force 22.124 kN. Comparison of differences between the highest levels with the lowest levels reached 4.86%. While the difference between the highest level with a square column with 1 hole was 14.24%. So that the more holes arranged in a pyramid would reduce the maximum impact force during a collision.

1. Introduction

A vehicle must meet the element of safety in the face of an accident when driving. The vehicle has a structure that can protect passengers in the event of a collision. The vehicle structure is divided into two spaces, namely the crumple zone and safety zone. Crumple zone is an area that is intentionally destroyed [1]. While the safety zone is an area that must be strong in protecting passengers. Crumple zone can absorb energy and reduce injury to passengers which called by crashworthiness. The crumple zone is located on the front rail area of a vehicle. In general, the shape of the front rail profile is circular, square or rectangular hollow and others. Many researchers had carried out experiments on the front rail area with material modifications, profile forms [2] and placed triggers which called by crush initiator [3,4]. The modification produced crashworthiness criteria such as maximum impact force and specific energy absorption when experiencing axial loads both quasi static and quasi dynamic. Estrada et al [5] had studied structures with bi-tubular profiles to absorb energy during collisions. The profile with aluminum 6063-T5 material was given a hole as a crush initiator. The test used a finite element simulation method with quasi static loading. Pirmohammad and Esmaelli [6] carried out an optimization of the square and octagonal bi-tubal structures using NSGA-II and ANN. The structure was given circle, hexagon and ellipse holes as crush initiator. The maximum impact force and specific energy absorption were known by the elemental method analysis with LS-DYNA code. In addition, heat treatment in certain areas could also be a crush initiator. This method of treatment had been carried out by Peixinho et al [7] in using an
aluminum square column. Tests were carried out with dynamic loads to obtain maximum energy and force absorption during collisions. Eyvazian et al [8] performed quasi static loading by using corrugated on circular tubes. Experimental and theoretical analysis was used to obtain energy absorption and maximum impact force when given axial loads.

Balaji and Annamalai [9] also conducted experiments and simulations on square hollow tubes with quasi static loading. The tube was given by a crush initiator in the form of a V-notch model and groove. Choiron et al. [10] modified the crash box using the initial fold. Finite element analysis was carried out to obtain a deformation pattern when given by dynamic axial loads. Using buckling initiator on a square tube was also carried out by Mashalkar and Tuljapure [11]. The tube was tested using finite element modelling with the help of Hyperworks and LS-DYNA. Loading used a quasi-dynamic method with variations in direction to get peak load and energy absorption.

Khalili et al [12] investigated thin-walled aluminum tubes when were given by dynamic loads. The test was conducted to determine the effect of energy transfer on trigger in the aluminum specimen. The square hollow structure was also investigated by Marzbanrad et al [13] with using the LS-DYNA numerical simulation method. The structure was given by a groove shaped hole with deep variation. This was done to obtain optimization with consideration of energy absorption and maximum impact force. Subramaniyah et al [14] had also conducted experiments on square tubes and circles with quasi static loading. Both tubes were given by holes as crush initiator to obtain maximum force and energy absorption. In addition, Mamalis et al [15] also carried out testing by using experimental and simulation methods on mild steel square tube. The tube was also given a crush initiator in the form of a hole to get a reduction of maximum impact force.

This paper discusses the use of crush initiator by modifying the pattern to form a pyramid arrangement. This arrangement was almost similar to the pattern from Dionisius et al [16] which used an inverted pyramid pattern. The objective of this paper was to determine the maximum collision force in quasi static loading. In addition, the smallest maximum impact force of some of these patterns is the best crashworthiness criteria in reducing passenger injuries. So that this research could be utilized by vehicle designers.

2. Methods
In achieving the desired results, there are several steps in this study as illustrated in Figure 1.

![Flow chart of steps](image)

**Figure 1.** Flow chart of steps.

### 2.1. Concept of crashworthiness
Crashworthiness is a structure that can absorb energy and reduce injury to passengers during an accident. Crashworthiness has several criteria, one of which is the maximum impact force ($F_{\text{max}}$). The impact force is generated from the structure of the vehicle. If it is too large, it can cause passengers to leave the area. The use of structures with thin wall thickness could absorb energy and reduce collision forces as examined by Abramowicz [17] and Tarlochan et al [18]. In this case, the smallest maximum impact force was the desired crashworthiness criterion.

Crashworthiness testing used a Universal Testing Machine (UTM) with 200 kN in capacities. The actuator on the UTM moved in quasi static loading with constant speed of 30 mm/min or 0.5 mm/s as shown in Figure 2b. Testing of specimens was carried out until 100 mm in deformation. The UTM would produce a graph of force and displacement so that the maximum impact force for each specimen could be known. This test was done by 3 times for each design. The test was based on the concept in Figure 2a where the UTM actuator was an impactor.
2.2. Tensile and composition test

Tensile testing was done to determine the characteristics of mechanical properties. The machine was Universal Testing Machine (UTM) which carried out in Mechanical Engineering Workshop, Politeknik Negeri Indramayu. The standard of this test used ASTM E8/E8M. The specimen was plate which taken from a square column with 0.8 mm in thickness as shown in Figure 3a. While the results could be seen in Figure 4 where was 192.80 MPa in yield strength and 267.5 MPa in ultimate tensile strength. These results were obtained through a tensile test as shown in Figure 3b.

Material composition testing used an Optical Emission Spectrometer machine with 20 elements in capacities. Material composition could be seen in Table 1. The type of material in this test was classified as low carbon steel because the number of carbon values was below 0.2%.

![Figure 2. Experimental of crashworthiness: a) Concept; b) By using UTM.](image)

![Figure 3. Tensile test: a) Preparation of specimen; b) Experimental of tensile test.](image)

![Figure 4. Graph of engineering and true stress.](image)
Table 1. Composition of elements in material of specimen.

| No. | Elements               | Value (%) |
|-----|------------------------|-----------|
| 1   | Carbon (C)             | 0,046     |
| 2   | Silicon (Si)           | 0,038     |
| 3   | Sulfur (S)             | 0,002     |
| 4   | Phosphorus (P)         | 0,016     |
| 5   | Manganese (Mn)         | 0,129     |
| 6   | Nickel (Ni)            | 0,01      |
| 7   | Chromium (Cr)          | 0,02      |
| 8   | Copper (Cu)            | 0,006     |
| 9   | Wolfram / Tungsten (W) | 0,001     |
| 10  | Titanium (Ti)          | 0,002     |
| 11  | Tin (Sn)               | 0,001     |
| 12  | Aluminium (Al)         | 0,027     |
| 13  | Antimony (Sb)          | 0,001     |
| 14  | Ferro / Iron (Fe)      | 99,715    |

2.3. Design of Experimental (DOE)

The specimen was a square column with a thickness of 0.8 mm which had 36 x 36 (mm) in section size with 200 mm in length. The column was given by hole 3 mm in diameter as a crush initiator. The position of the hole was at 10 mm from the end of the specimen which called by NA. Then adding the same diameter hole was done by forming a pyramid arrangement. These additions were carried out in stages called first level to third level in design as shown in Figure 5.

3. Results and discussion

Crashworthiness testing in this paper was carried out to determine the maximum impact force in specimens with pyramid arrangement. The test produced progressive buckling up to 100 mm in deformation as shown in Figure 6. The total time of this deformation was 200 seconds. The test produced 4 folds where the value of the maximum force is at the first folding which called by folding mechanism. This could also be seen in Figure 7 where there were 4 peak values for each specimen condition. Some of the peak values were the beginning of folding that occurred in each specimen during quasi-static loading.

Figure 5. Design of experimental.
Based on the graph in Figure 7, the maximum force value for each condition could be seen in Error! Reference source not found. First level to third level design had a decrease in maximum collision force from 23.255 kN to 22.124 kN or 4.86%. While from the NA design to third level, the maximum impact force decreased by 14.24%. This showed that crush initiator with multilevel pyramid arrangement could reduce the maximum impact force during a collision.

The decrease in maximum impact force was caused by the location of different folds in each design. The difference could be seen in Figure 9. The first fold on the NA design was located in the area of 1 hole. While the level 1 design was in the area of 20 mm from the end of the specimen where there were 2 holes each side. The level 2 and level 3 designs also experienced initial fold in the area of 3 holes and 4 holes in parallel. This means that the location of the fold will depend on the area with the number of parallel holes. Therefore, the reduction of maximum impact force occurred in this study.

Based on the stress theory proposed by Khurmi and Gupta [19] that the force was the multiplication between stress and area during axial loading. Figure 10 shows that the area in each design is not the holes area. If the area is smaller, it will produce a small force and vice versa. So that the force produced when axial loads will be directly proportional to the area of each specimen.

**Figure 6. Progressive buckling.**

**Figure 7. Graph of force and deformation during crashworthiness test.**
Figure 8. Maximum impact force of each condition.

(a)  
(b)  
(c)  
(d)  

Figure 9. Initial buckling in design of: a) NA; b) 1st level; c) 2nd level; d) 3rd level.

4. Conclusion
Crashworthiness testing with quasi static loading had been done on thin-walled square column specimens. The specimen was given a crush initiator which began with 1 hole. Then the hole would be added to form a pyramid arrangement. This arrangement was identified as the first to the third level. The conclusion of the test was that the maximum impact force had decreased by 14.24% from the specimen with 1 hole to the third level of pyramid arrangement. The decrease also occurred in the first level of pyramid arrangement to third level that was 4.86%. So that the best crashworthiness criteria were in the level 3 pyramid arrangement which has the smallest maximum impact force.

Figure 10. Area in NA design.

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