Energy Absorption Characteristics for Corroded Circular Aluminum Tube

[1]Nizam Yob and [2]K.A. Ismail
[1]School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Main Campus, 02600 Arau, Perlis, Malaysia
[2]School of Manufacturing Engineering, Universiti Malaysia Perlis, Pauh Main Campus, 02600 Arau, Perlis, Malaysia
E-Mail: nizamyob@gmail.com

***Abstract*--** **This paper presents experimental work on quasi static compression test of corroded circular tubes of aluminum AA 6063 T5. A new apparatus was developed to prepare corroded specimens. A lot of 26 specimens were prepared with variable exposure time to corrode, then to be compressed via universal testing machine. Values of P_{max}, P_{mean}, and total energy absorption are reduced significantly when exposure time to corrode been prolonged, because of mechanical properties will be reduced when corrosion level at the worst. Several empirical models were established for corroded circular aluminum tubes with variable exposure time to corrode.**

***Index Term*--** **Energy absorption, thin walled tubes, corrosion, ageing material**

1. INTRODUCTION

Safe design of components and systems for vehicle is of interest to general public. The impact of transport vehicle as an example, is an unfortunate but a common daily occurrence. It is becoming apparent that, in the future, transport structures will have to be designed to minimize effects from impacts and crashes. Several works have been developed by previous researchers and engineers to investigate the thin walled tube as an energy absorption structure and optimize the design to get better performance for energy absorption[1]–[6]. Since investigation in the thin walled structure is very wide ranging, still not enough information with regards to studies on energy absorption against degrading or ageing material of specimen.

The ageing processes (metal fatigue, corrosion) of structure materials have the influence on vehicle safety. According to Grikevicius and Ziliukas[7], over 80% of registered cars in Lithuania are older than 12 years and in these cars defects of the vehicle body structural components (corrosion, deformation, cracks) exceed 5%. A report from Malaysia Institute of Road Safety Research (MIROS) said, a recurring problem of road crashes and multiples injuries and fatalities has boosted the need for effective and efficient plus reliable and safe public transportation in Malaysia. In depth analyses on numerous heavy commercial passenger vehicles (HCPVs) crashes by the MIROS found that there was significant number of HCPVs suffering from degraded safety structures that mechanically failed during collision. These collisions have resulted in multiple fatalities and injuries[8].

For this concern, this study intends to investigate and measure performance of corroded energy absorber part in term of energy absorption characteristic. The aims of this paper are, (a) to develop energy absorption characteristic of the corrosion specimens via compression tests with variable exposure time to corrode and (b) to develop empirical models of the corrosion specimens for peak force (P_{max}), mean crushing force (P_{mean}), crush force efficiency (*CFE*), and specific energy absorption (*SEA*).

1.1. Effect corrosion on mechanical properties in material.

Mechanical properties is the most important characteristic in order to identify the strength of material, especially in mechanical tensile properties. As a rule of thumb, if that certain material possesses a high value of yield strength and ultimate tensile strength, that makes it the strongest material. Griskevicius and Ziliukas[7] conducted mechanical tensile testing that result showed ratio between deformation energy between corroded front side members and un-corroded front side members is 1.36 times.

The relationship between corrosion severity and mechanical properties degradation have been studied by Appuhamy et al.[9]. That study showed mechanical strength of steels decreased when the level of corrosion become worse. Chen et al.[10] analyzed the strength and deformability of steel specimens subjected to random non-uniform general corrosion and tensile load. Four specimens were prepared, non-corroded specimen and three different cases of different corrosion level as renamed Intact, Case 1, Case 2 and Case 3, where its refer to the specimens subjected to the three different levels of general non-uniformly distributed corrosion with the average plate thickness of 7.380mm (7.8%), 6.554 (18.1%) mm and 5.852 (26.9%) mm, respectively. They found the tensile strength decreases with the increase of the corrosion deterioration. A 8.1% of the strength is lost when the specimen is subjected to 7.8% general non-uniform corrosion, after that the strength loss still decreases with the increase of the corrosion deterioration, but with a lower changing rate, that it varies from 19.0% to 20.0% as the corrosion changes from 18.1% to 26.9%. The severe corrosion results in less elongation.

1.2. Effect corrosion on energy absorption by finite elements (FE) and experiments.

Ageing effects such as corrosion damage and consequently the degradation of mechanical properties of steel will influenced the performance of crashworthiness. Iskandar and Li [11] have been studied comparison between new bus condition and aged bus condition after having rollover test. The rollover test following UNECE Regulation 66[12] and Figure 1 shows full rollover test according UNECE R66. New bus structure generally remained intact and residual space envelope is not penetrated, therefore it passed the test. On the other hand, aged bus after the test, upper structure clearly penetrating residual space. Hence the aged bus, obviously failed the test.

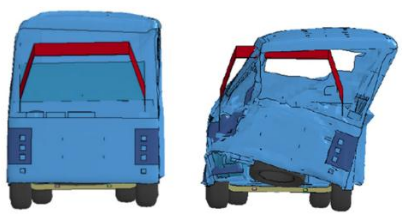


Fig. 1. Left-New Bus after rollover test. Right-Aged Bus after rollover test[11].

Grikevicius and Ziliukas[7] found that corrosion of front side member could decrease the value of energy absorption to 1.6 times, and also the difference of FE calculated total energy absorption between corroded front side member and modern advance vehicle concepts (using dual phase steel, DP 500/800) is approximately 3 times.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

Material and experimental procedure are presented in this section. Table 1, gives dimension of test specimens. Ratio R/t and L/D for circular tube was 11.99 and 5.33 respectively. The chemical composition and material properties for this tube are given in Tables II and III respectively

Table I
Dimension of Aluminum Tubes AA 6063 T5.

Length [mm]	Thickness [mm]	Outer Diameter [mm]	Weight Before Accelerate Corrosion Process [g]
203.2±0.1	1.59±0.1	38.10±0.1	91.40±0.17

Table II
Chemical Composition of Aluminum Tubes AA 6063 T5.

%	Cu	Fe	Mg	Mn	Si	Ti	Zn	Cr	Other	Al
Min*	0.01	0.17	0.48	0.03	0.44	0.01	0.01	0.01	0.10	The rest
Max*	0.10	0.17	0.48	0.03	0.44	0.01	0.10	0.10	0.10	

*All in weight %

Table III
Mechanical Properties of Aluminum Tubes AA 6063 T5.

Yield Stress	Ultimate Tensile Stress	Density	Elastic Modulus
$\sigma_{0.2}$(MPa)	σ_u(MPa)	ρ(kg/m^3)	E(GPa)
118	152	2.71 x 10^3	69

2.1. Accelerate Corrosion Process

A setup apparatus of accelerate corrosion process, consists of a container, anode (specimen), cathode, power supply and test solutions. The diagram of this apparatus as shown in Figure 2. The container itself must not induce corrosion attack due to not disturbing the process of corrosion. A good rule of thumbs, is to use 40cm^3 of test solution for every 1cm^2 of exposed area. In this research, a 152.4mm x 152.4mm x228.6mm plastic container and the specimens were immersed until left 60mm length of specimen, hanging on supporting beam. Cathode was zinc plate approximately 152.4mm x 215.9mm size and connected with negative terminal on power supply. Cathode was hanging on supporting beam. Anode was the circular aluminum tube specimen and connected with positive terminal on power supply. Power supply PS 3005A from Dazheng was used in this study, and the output of current and voltage can variable or adjustable 0 to 5A and 0 to 30V respectively. The test solution was concentration 0.005 kg/l of natrium chloride (NaCL) in 4 liters water. For this study, the voltage was setup 12V, and time exposure will be varied as 4, 8, 24, 48, 72, 96 or 120 hours.

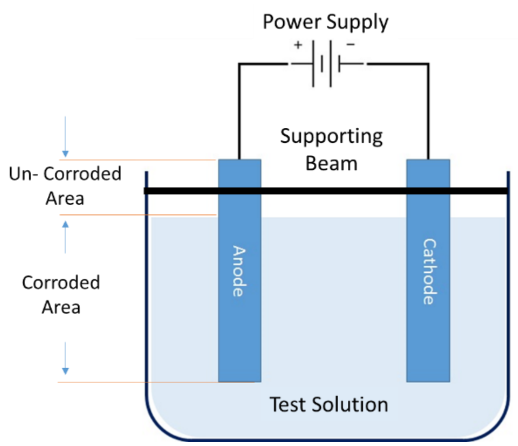


Fig. 2. Diagram for Apparatus Accelerate Corrosion Process.

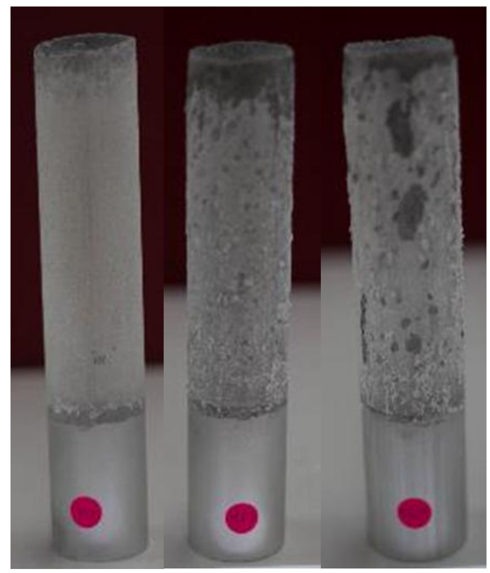
2.2. Compression Test

After accelerate corrosion process, the test specimens were weighted and then compressed using Shimadzu universal testing machine with loading capacity 250kN. Loading rate and total crushing displacement were set at 5 mm/min and 100mm respectively. This loading rate considered quasi static since the strain rate is in the range of 10^{-4} s^{-1}. Based on chart developed by Guillow et al.[6], circular tube was expected having collapsible mixed mode. This is in agreement with the earlier work by Yob et al. [13](Figure 3).

Fig. 3. Mixed mode deformation pattern for virgin tube by Yob et al.[13].

3. RESULTS AND DISCUSSIONS

Table 4 shows tests result for compression of aluminum tubes. Four set of specimens have been prepared for each parameter (time of exposure). Effect of exposure time to corrode on the specimens is shown in Figure 4. Physically, the tube deteriorates further as the exposure time increases[9], [10], [14]. Figure 5 shows percentage of weight loss against exposure time to corrode. The percentage weight loss increases when exposure time is increased[10], [14], [15]. Total energy absorption shown in Table 4 is a total energy absorption at 80mm displacement when the tube densified. The phenomenon of densification will be explained next.



(a) (b) (c)

Fig. 4. Specimen condition after corrosion process under various exposure time to corrode (a) 24 hours, (b) 72 hours, and (c) 96 hours.

Table IV
Average Data for Compression of Aluminum Tubes.

Time of Exposure	Weight Loss [g]	P_{max} [kN]	P_{mean} [kN]	Total Energy Absorbed [J]	*CFE*	*SEA* [kJ/kg]
4 Hours	0.73	32.99	17.48	1398.62	0.53	15.43
8 Hours	1.50	29.93	16.44	1315.53	0.55	14.65
24 Hours	6.85	18.49	11.87	949.39	0.65	11.22
48 Hours	6.68	13.51	10.30	823.71	0.77	9.72
72 Hours	13.10	9.31	7.79	623.50	0.84	7.95
96 Hours	19.10	5.93	5.66	452.91	0.99	6.21
120 Hours	24.39	4.53	4.50	360.14	0.98	5.28

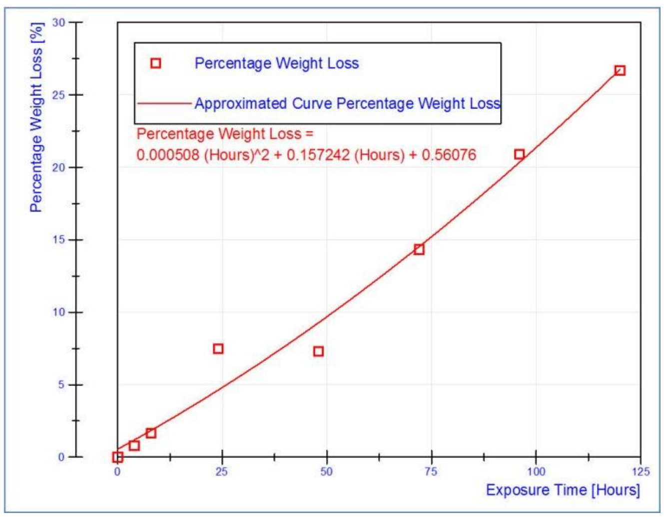


Fig. 5. Percentage weight loss against exposure time to corrode.

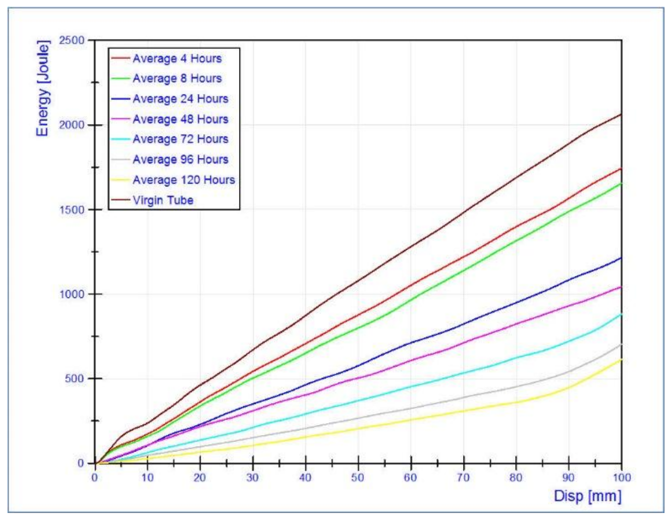


Fig. 7. Energy against displacement.

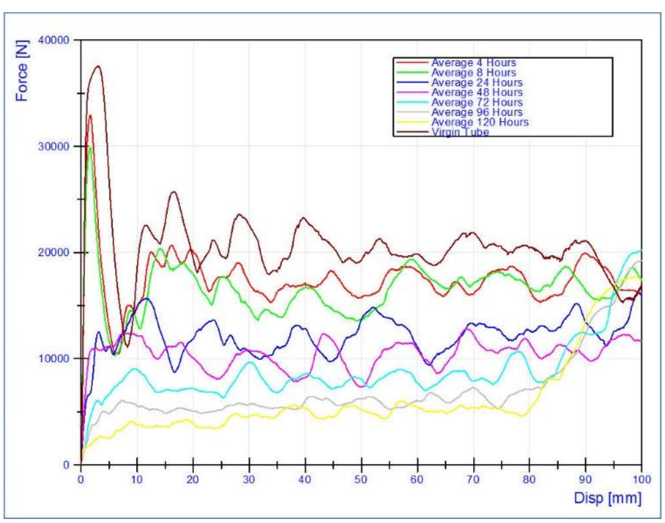


Fig. 6. Force against displacement.

Figure 6 shows response of force against displacement for all corroded conditions of tubes including virgin tube, meanwhile Figure 7 shows comparison of total energy absorbed. Starting from virgin tube to 48 hours' time to exposure specimens, the tubes show linear increase in force until maximum load (peak), but as instability develops it falls off rapidly until a first fold is developed. A series of fluctuations about mean force develops, the peaks and troughs being directly related to the form and folding at the various buckling levels[1], [3], [5], [16]. For specimens from 72 hours to 120 hours' time to exposure, initially the force rise until tube behaved plastic deformation (first fold developed) and leveling at certain force, then tube having densification after approximately 80mm deformation due to the folding developed at un-corroded area. Figure 8 showed more detailed about deformation pattern.

Comparison between virgin tube and 120 hours corroded specimen gives significant reduction of P_{max} to only one - eight of that of the virgin tube. Meanwhile, P_{mean} are reduced approximately 4.5 times than the virgin tube In the meantime, energy absorption are reduced almost 4 times than the virgin tube. These results showed, to proof hypothesis which are, the mechanical properties of material will reduce when material degrading. To support more evidences, studied from Chen et al.[10] and Appuhamy et al.[9] showed mechanical properties will reduce when corrosion level at worst. Figure 9 and 10 show relationship of force against exposure time to corrode and energy against exposure time to corrode respectively. Also plotted is the result for virgin tube (exposure time of 0 hour)[13].

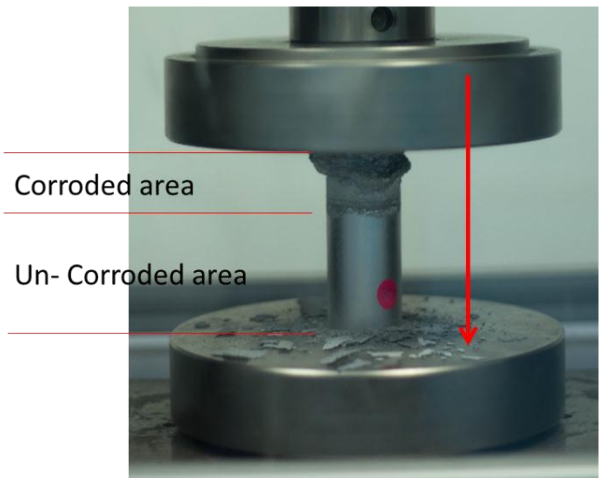


Fig. 8. Specimen C33, having densification after 80mm deformation, folding pattern reached un-corroded area. The red arrow indicates direction of axial loading.

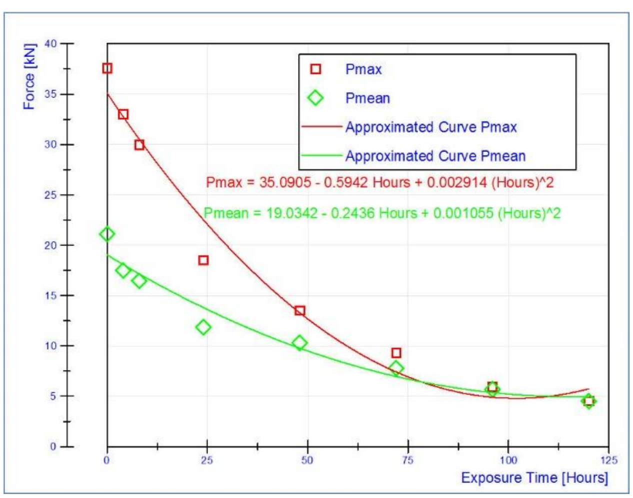


Fig. 9. Relationship between force and exposure time to corrode.

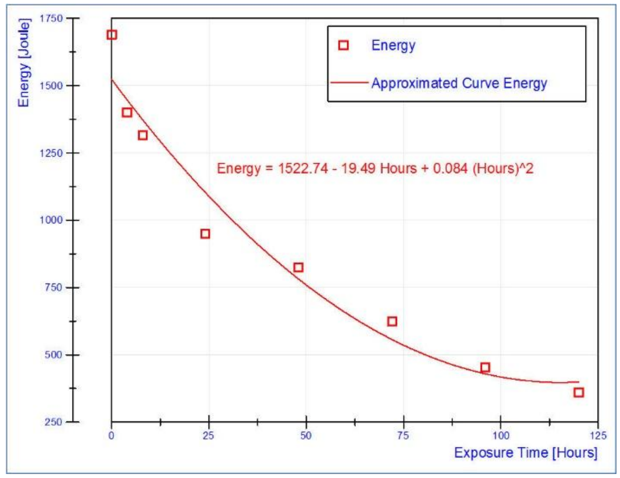


Fig. 10. Relationship between energy and exposure time to corrode.

Figure 11 and 12 show relationship between *CFE*, *SEA* and exposure time to corrode respectively**.** Crush force efficiency (*CFE*) increases when exposure time to corrode increased. When the exposure time to corrode set exceeding 75 hours, *CFE* values are closer to one since P_{max} and P_{mean} values are almost similar (Figure 9). On the other hand, Specific energy absorption (*SEA*) decreases when exposure time to corrode increase because of total energy absorption decreases significantly.

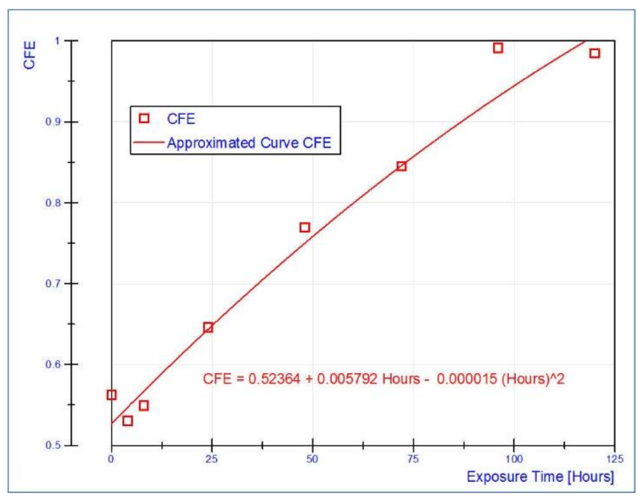


Fig. 11. Relationship between *CFE* and exposure time to corrode

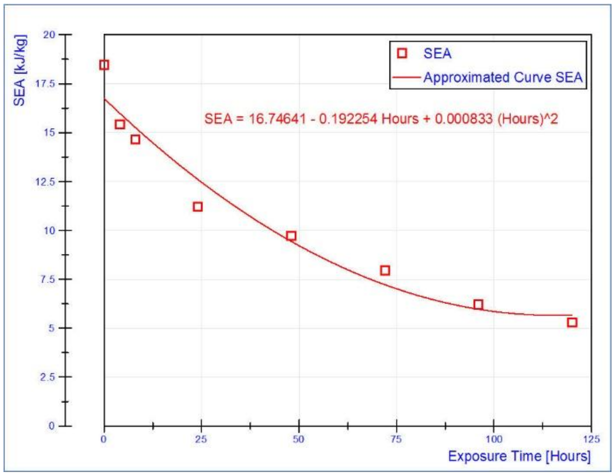


Fig. 12. Relationship between *SEA* and exposure time to corrode

4. CONCLUSION

Experimental quasi static compression test result on corroded circular aluminum tubes are presented in this paper. Then the test results were analyzed and compared to the previous work by Yob et al.[13]. The main conclusion from this study can be summarized as follows:

a) P_{max}, P_{mean}, and total energy absorption are reduced significantly when exposure time to corrode been prolonged. Mechanical properties will be reduced when corrosion level at the worst or exposure time to corrode been prolonged, and these result were supported by the previous study done by others researcher.

b) This study also develops several empirical models regarding energy absorptions characteristic of corroded speciemns with variable exposure time to corrode. These are;

i) Empirical model P_{mean} against exposure time to corrode:

$$Pmean = 19.0342 - 0.2436(Hours) + 0.001055(Hours)^2$$

ii) Empirical model P_{max} against exposure time to corrode:

$$P\max = 35.0905 - 0.5942(Hours) + 0.002914(Hours)^2$$

iii) Empirical model total energy absorption against exposure time to corrode:

$$Energy = 1522.74 - 19.49(Hours) + 0.084(Hours)^2$$

iv) Empirical model *CFE* against exposure time to corrode:

$$CFE = 0.52364 + 0.005792(Hours) - 0.000015(Hours)^2$$

v) Empirical model *SEA* against exposure time to corrode:

$$SEA = 16.74641 - 0.192254(Hours) + 0.000833(Hours)^2$$

5. ACKNOWLEDGEMENT

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Nizam Yob was born in Pontian, Johore. He was experienced more than 6 years in Automotive Engineering especially in Passive Safety Engineering. Graduated on Bachelor Engineering in Saitama University, Japan 2007. His field research on automotive structures, development on passive safety product engineering.