Deterioration of Crashworthiness Performance of Aged Structure

I. Abdul Hamid, and Q.M. Li

***Abstract*—**Corrosion and fatigue are known as ageing factors, influencing and deteriorating structural integrity and safety. However, the ways that these ageing factors influence and deteriorate structural crashworthiness require further research. Corrosion causes the reduction of structural thickness and degradation of mechanical properties while fatigue damage introduces new fracture surfaces and the degradation of mechanical properties. Without considering ageing rate, ageing effects with several sets of escalated severity are introduced to a bus structure, which are tested numerically in a crash scenario to find their different crashworthiness responses. Case study used is a finite element model of a bus. It is tested according to UNECE R66 standard. Results show that structural crashworthiness degrades with the increase of ageing effects.

***Keywords*—**Ageing effects, ageing factors, deterioration, structural crashworthiness.

I. Introduction

STRUCTURAL integrity is studied and investigated thoroughly by researchers. The purpose is to make sure that the structure properly plays its role in supporting the design and service loads reliably and safely within its life span. With proper maintenance and repair, a structure may be able to extend its services and operates beyond its original design life time. However, ageing is an unavoidable natural process which deteriorates the strength of the structure and reduces its service life.

Structural crashworthiness, on the other hand, is a study on how well the structure can retain its strength against impact load within the defined safety region. In a more specific area, vehicle crashworthiness for example, is defined as the ability of the vehicle structure to protect its occupant during the impact. The assessment of structural crashworthiness should be made as early as in conceptual and detailed design stages, whereby the structure prototype is tested numerically and experimentally to see how good (or how bad) is its performance against safety standard. From the above definitions, one can see that there is a gap of knowledge between the two. Structural integrity is focusing on the structure's performance against service load along its service life, but does not look into how the structure responds to the unexpected impact load that may accidentally apply to it, especially for a aged structure with deteriorated strength. While from structural crashworthiness point of view, it is focusing on crashworthiness performance at the very early age of the structure, but its performance after some time in service is unknown, or at least not being systematically determined.

The purpose of this study is to fill these gaps by looking specifically into how well aged structure would respond to impact load. As the field of crashworthiness is normally applied to vehicle safety, we choose a land vehicle as our case study. Among land vehicles, commercial vehicle like buses are one of the main focus of researchers as it involves many occupants inside it and its structural failure during crashes normally cause many fatalities. The study uses finite element bus model which is set up for rollover crash test according to UNECE Regulation 66 standard. The structural properties are set at five different levels of descending order of material strength representing ageing effects and each of them is tested. The strengths are reduced by changing the dimensions of the structure and changing the properties of the materials. This study is not looking into the rate of change of structural properties.

II. Literature Review

A. Effect of Ageing on Structure

Ageing, as defined by International Atomic Energy Agency (IAEA), is the continuous time dependent degradation of materials due to normal service conditions, which include normal operation and transient conditions [1]. In other words, materials are affected by service environment and service (or operating) condition, and these two factors degrade material properties through time [2]. Service environment causes corrosion damage on materials whereas service condition causes fatigue damage on materials [3]. Corrosion causes reduction of material thickness and therefore effects materials mechanical strength [4]-[5], while fatigue causes reduction of mechanical strength especially at metal surface and stress concentration areas like welded joints [6]. At fatigue limit, the crack initiates and propagates at these areas, further reducing the overall structural strength.

The ageing mechanisms can be prevented or mitigated by maintenance practice. For example, corrosion can be prevented by applying corrosion protection on metal surface and fatigue crack can be slowed down by stop drill hole

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technique or material change. As our focus is the effect of ageing, this aspect is not discussed in the present work.

B. Corrosion Damage

In ageing study, normally two types of corrosion are discussed; general corrosion (or uniform corrosion) and pitting corrosion. General corrosion reduces structural thickness uniformly while pitting corrosion causes degradation in local regions [7]. Experimental results show that corrosion reduces material strength [4]-[5], and this was also shown in numerical results [7]-[8]. For example, Figure 1 shows how general and pitting corrosions affect the strength behaviour of the materials. Thicker general and pitting corrosions cause more reduction of strength at various degrees. The reduction of ultimate strength can be concluded to be significant due to corrosion.

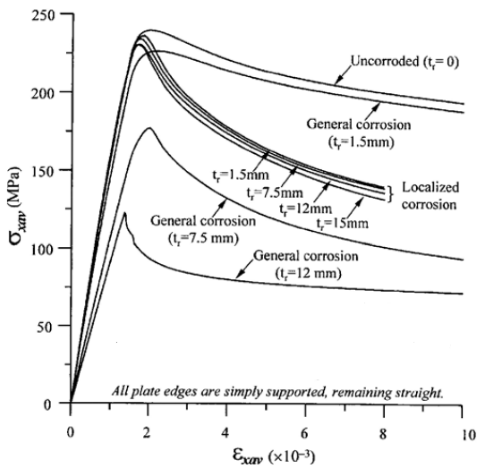

Fig. 1 Effect of general and pitting corrosions toward reduction of materials ultimate strength [8]

C. Fatigue Damage

Buses are being operated under various load conditions, on different roads, under different traffic conditions and driven by drivers with different attitudes [9]. Under many variables of service conditions, the structural components at a bus experience cyclic damage. This causes fatigue which affects its material mechanical properties [6]. Beyond fatigue limit, crack initiates and propagates.

From experiments and simplified model in [7], it is shown that with the increment of crack size, the ultimate tensile strength of plates decreases. Figure 2 shows the variation of the ultimate tensile strength of plates as a function of the crack length.

Fatigue cracks initiated in the stress concentration areas of the structure, especially at the welded connections. Under repeated cyclic loading and sometimes extreme loads, cracks may grow and propagates in an unstable way. Together with deterioration of mechanical strength, cracks remain undetected over time and eventually lead to catastrophic failure of the structure.

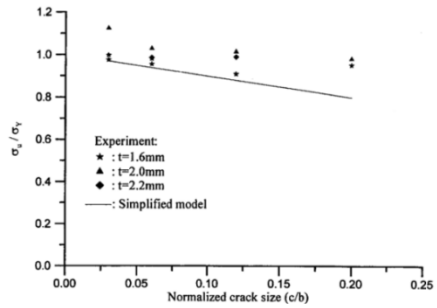

Fig. 2 Variation of the ultimate tensile strength of plates as a function of the crack length [7]

E. Effect of Ageing on Structural Crashworthiness

From real, in-depth crash investigation of bus rollover cases, it can be seen that aged buses experience severe, and sometimes catastrophic damages and leads to high number of occupant fatalities. Figure 3 shows a real rollover crash [9], involving 6 fatalities, 3 severely injured and 19 with minor injuries. The bus was 16 years old. Figure 3(a) shows the total collapse of bus roof, and Figure 3(b) shows the severely corroded frames of the bus.

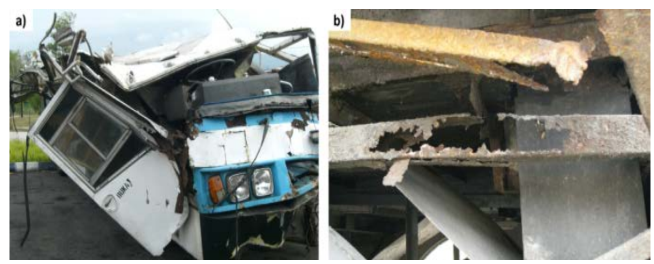

Fig. 3 Rollover crash of aged bus

It remain unknown on how much ageing effect contributes to the severity of the damage because so many factors need to be considered e.g. safety standard design compliance, crash configuration and crash impact loading. Therefore, it is necessary to study, under controlled environment, on how ageing factors deteriorate the structural materials, and how much this deterioration affects the overall performance of bus structural crashworthiness. This can done by applying set of ageing effects with escalated severity on the finite element bus structure model, and then crash test is conducted on the bus model.

III. METHODOLOGY

A. Finite Element (FE) of Vehicle Model

The FE model of a bus chosen for this study is developed by [10], and can be downloaded from free domain at [11]. It is a model of CONTRAST bus assembled by VEST-VUSCAR Company, a single high-deck floor bus for district use. This model was selected because it represents the commercial bus commonly used in developing countries, whereby the operation sometimes beyond its service life period.

The model consists of 111629 nodes, 117208 elements, 307 parts and 28 type of materials. It has been tested at different stages of its development, including the working mechanism of the steering system and suspension. Material model used for bus frame structure are basically low carbon steel or mild steel.

R66 crash test procedure [12] was set to the bus by adding tilting platform with wheel supports act as axis of tilting. The platform is tilted at 49 degrees at unstable equilibrium, so the rollover can starts at the beginning of the simulation to shorten simulation time. Imaginary residual space envelope as specified in the regulation was also created to indicates pass/fail rollover result. For example, if the outer structure penetrates into the residual space, the test failed. The bus 'fall' on the rigid wall, act as concrete ground surface. Figure 4 shows the bus rolled over on the concrete ground according to R66 procedure.

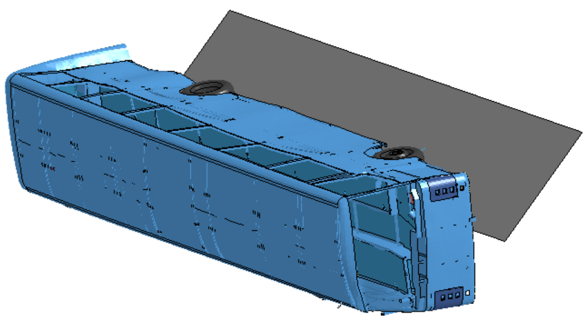

Fig. 4 Rollover test on the CONTRAST bus according to UNECE R66 procedure

The bus frame structure can generally be divided into 3 sections; lower, side and upper frames, as shown in Figure 5(a), (b) and (c), while in Figure 5(d), it shows the overall frame. In Figure 5(e), the elements at structural joints are shown. Each section experience different level of corrosion due to different environment condition. It is justifiable to assume that lower frame is experiencing the worst corrosion damage while in service because it is exposed to water splash which may contained corrosive substance, and the upper frame experience the least corrosion damage. The same goes to fatigue damage, as the lower frame is directly receiving excitation and cyclic loading from the suspension system, while the upper frame receive the least.

Ageing effects applied to the bus structure are adjusted until it give rollover test results that can be categorized into the following categories: minor damage, major damage, severe damage and catastrophic damage.

A. *Corrosion Damage on Finite Element*

As stated earlier, corrosion damage is basically divided into general and pitting corrosions. In finite element, general corrosion can be applied on structural surface by reducing the thickness. For pitting corrosion, it can be ideally applied on metal surface at different intensities. Figure 6 shows an example of idealized pitting corrosion intensities considered in [7].

However, this method is quite impractical and tedious if to be applied on the whole bus structure. It is therefore decided to use 'equivalent' general corrosion-based approximation to represent both type of corrosion [8]. Reduction of thickness is followed by reduction of mechanical strength of materials, as explained and shown in previous work [3].

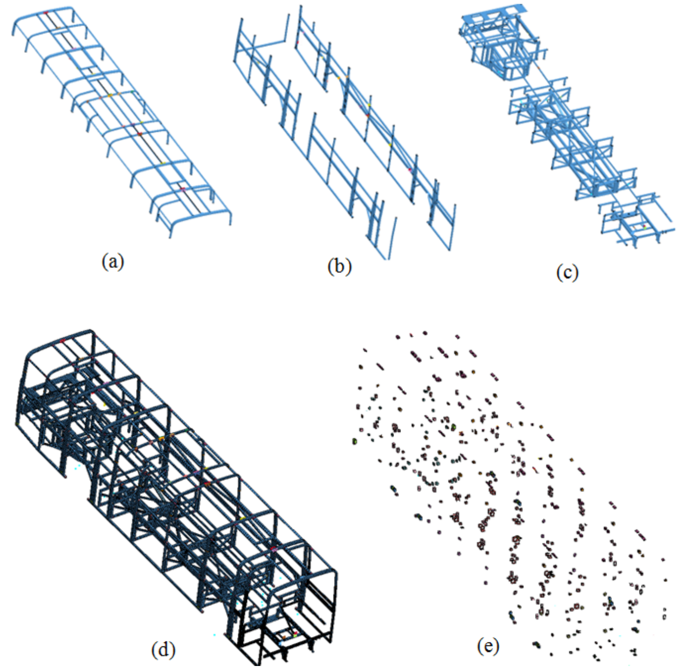

Fig. 5 (a) Upper frame (b) side frame (c) lower frame (d) Overall frame (e) elements at joints

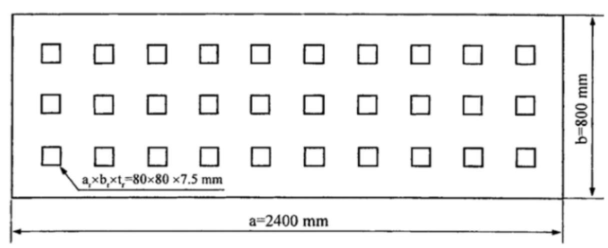

Fig. 6 Example of pitting corrosion intensity of 10% at 7.5mm thickness [7]

B. *Fatigue Damage on Finite Element*

Cyclic loading causes fatigue which reduces mechanical strength of materials. The strength is further reduced when crack initiates and propagates. The reduction of mechanical strength is represented by reducing yield strength of materials according to categories mentioned before. Fatigue crack itself is pessimistically assumed to occur on every joints of the structure. This can be represented by creating a new part from the existing element, close to the joint, as depicted in Figure 7 (a). It also shows the width of an existing element is the same as the width of the square tube. As for the new defined part, it can be divided into several smaller elements. The thickness of these element(s) can be changed accordingly to represent the length and thickness of fatigue cracks.

However, the method explained above is impractical to be done to all joints of bus structure because of the time consuming. The simpler way is to select the whole end element next to the joint and apply the thickness and strength

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reductions on it, as shown in Figure 7(b). Since the crack length is fixed according to element size, the 'equivalent' crack damage can be compensated by adjusting the thickness accordingly. Even though the size of crack seems 'much' larger than the supposed size, the effect of crack can be reasonably considered. This method is expected to give about the same effect on the joint during impact. For a large complex structural system, these differences can be considered as insignificant. The total number of joints are 443 and was shown previously in Figure 5(e).

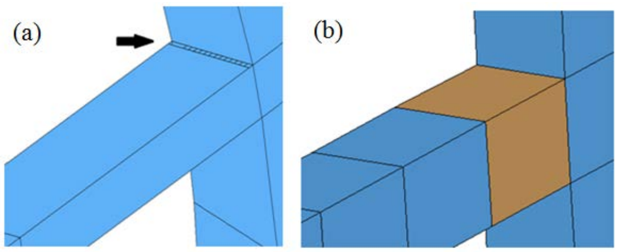

Fig. 7(a) Ideal representative of fatigue crack (b) Practical representative of fatigue crack

C. Assumptions and limitations

Besides the assumptions mentioned above, other assumptions are highlighted, as follows:

1. In the FE bus model, the square tube frames were connected at joints by using the same node, not by welding. It means the connection strength between the structures are (assumed to be) equivalent to the strength of materials itself, even though in reality, the strength (of welded joint) might change over time. It is therefore reasonable to 'create' fatigue crack at joints by reducing thickness of end nodes to represent the damage normally occur at the Heat Affected Zone (HAZ).

2. Bus skin does contribute to overall crashworthiness performance, as its deformation absorb about 10% of the total internal energy [13]. However, the deterioration of materials of skin part is ignored in this study to make the modeling easier.

3. It is assumed that the variation of ultimate tensile strength of plates as shown in Figure 2 can also be applied to other shapes like square tube, which are commonly used in the bus frame structure.

4. The general corrosion damage starts immediately on the structural surface with the assumption that the anti-corrosion system (e.g. coating) has lost its effectiveness.

5. Fatigue cracks may also arise at stiffened steel panel component, at the centre of the panel, and from localized corrosion. However this aspects are not considered in the present work.

6. For the current work, it is assumed that the reduction of material thicknesses and yield strengths are according to percentage.

D. Levels of Materials Deterioration

Based on the above conditions, assumptions and limitations, the levels of materials deterioration on bus structure due to ageing process, in descending order, are summarized and shown in Figure 8. The reduction levels are not made in uniform scale, so we can show how the bus can crash at its most possible severe condition. (Note: Upper Frame (UF), Side Frame (SF) and Lower Frame (LF)).

Level	Thickness reduction (%)					
	At general frame surface			At joints		
	UF	SF	LF	UF	SF	LF
1 (original condition)	0	0	0	0	0	0
2	40	45	50	45	50	55
3	55	60	65	60	65	70
4	70	75	80	75	80	85
5	80	85	90	85	90	95

Level	Yield strength deterioration (%)					
	At general frame surface			At joints		
	UF	SF	LF	UF	SF	LF
1 (original condition)	0	0	0	0	0	0
2	20	25	30	25	30	35
3	25	30	35	30	35	40
4	30	35	40	35	40	45
5	40	45	50	45	50	55

Fig. 8 Levels of materials deterioration based on percentage of thickness reduction and yield strength deterioration

IV. Results And Discussion

Results of rollover test of deteriorated materials are shown in Figure 9. Figure 9(a) is the original condition of the bus before the test. Figure 9(b) shows the original condition of the bus after the test (Level 1). The frame structure is seen dented but at a very small degree and the bus passed the test. In Figure 9(c), the frame is dented very near to the residual space envelope (in red) but still pass the test. This can be categorized as minor damage (Level 2). However, if ageing effects are applied ideally, it might fail the test. In 9(d), the bus experience major damage as the frame structure penetrated into the residual space envelope and failed the test (Level 3). In 9(e), the residual space envelope was penetrated at a higher degree and is considered as severe damage (Level 4). The bus experiencing catastrophic failure in 9(f) (Level 5).

The catastrophic failure category is considered to imitate the real rollover crash and for demonstration purpose. It shows how ageing of structure can severely influences the overall bus structural crashworthiness. Ageing damage may not be that severe that it may give these catastrophic crashworthiness results. However, this study can be a valuable input for future studies when it comes to the assessment and comparison with other damage severity factors. The bus skin is still intact because its properties were unchanged.

By considering severity and catastrophic crashworthiness condition, pass/fail criteria of R66 standard may require further classification.

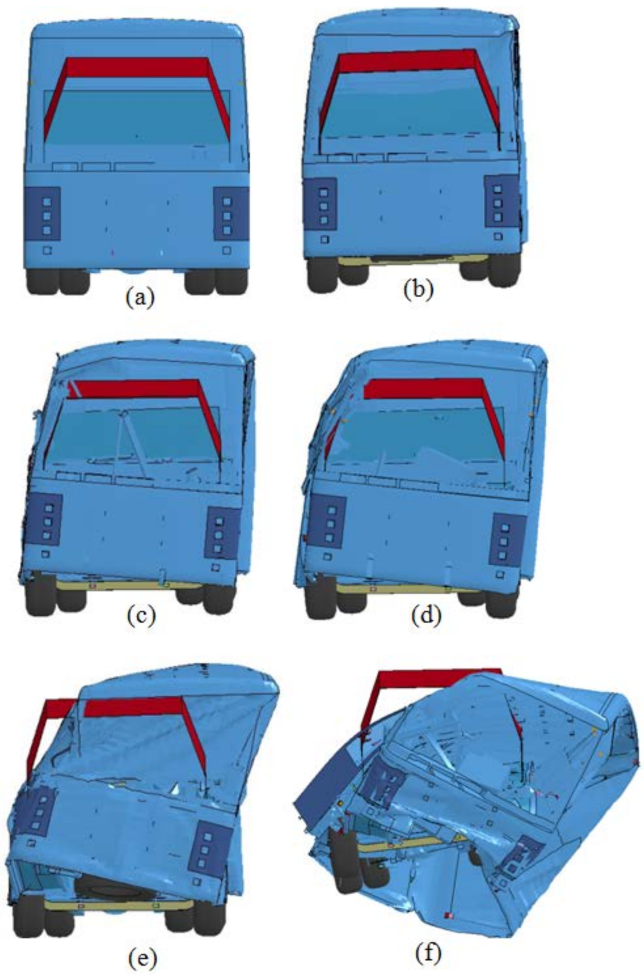

Fig. 9 (a) Original bus condition (before rollover)
(b) Original bus condition (after rollover) (c) Minor damage (d) Major damage (e) Severe damage (f) catastrophic damage

Especially for failure criteria, level of penetration on the residual space envelope can be further classified, for example major, severe or catastrophic. This is relevant especially to evaluate the strength of aged buses.

V. Conclusions And Future Works

Ageing process deteriorates structural integrity and safety, including structural crashworthiness as shown in this work. Ageing effects like corrosion, fatigue and mechanical properties deterioration can significantly reduce the original structural strength, including the strength to withstand impact load. In case of vehicle crashworthiness performance, the severity of crash results of the bus can be categorized into minor, major, severe and catastrophic, depending on the structure materials deterioration level.

Further analyses on the comparison of structural responses toward impact loading will be made at frame component and element levels. The input ageing effects that give categorical crashworthiness performance will be analyzed and time factor will be considered. Results will be analyzed using methods like statistical or modal uncertainty and sensitivity analysis.

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