Ageing Effect on Crashworthiness of Bus Rollover

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International standards related to protection of occupants in rollover accidents are generally applied on new vehicles and regulated for design approval. However, there is no standard regulation governing rollover crash performance of aged vehicles and no proper systematic test to monitor it. It is known that vehicle structural integrity deteriorates after years of operation undergoing various service environments and conditions. The scenario is worsen if the vehicle is poorly maintained and still in operation beyond its lifespan. These factors directly influence the vehicle crashworthiness level and affects its safety. The present paper attempts to show how ageing factors like corrosion and deterioration of mechanical properties may change the overall vehicle structural strength and hence its crashworthiness performance. As a case study, rollover analysis according to European standards (UNECE R66) was set up on a finite element bus model using LS-Prepost® and simulation was performed using LS-DYNA®. Different levels of condition due to ageing effect were included in the model to examine the changes of rollover performance of the bus. Aged bus rollover studies from real world crashworthiness investigation in Malaysia were referred for comparison to support the argument. Result shows that ageing factors directly influence the performance of vehicle crashworthiness.

Keywords: Crashworthiness; Rollover analysis; Aged vehicle; Ageing factors

1 Introduction

Real-world or actual crashworthiness investigation on roll-over crash of buses in Malaysia showed poor performance of bus structures. The failure of the structure to maintain its surviving space causes severe and fatal injuries to the occupants trapped inside. One of the possible reasons for its happening is ageing factor. Structural strength is deteriorated over time due to the exposure to service environment, service condition and manufacturing/fabrication stresses that lead to fatigue, corrosion and change of mechanical properties of structure materials.

The above problem motivates this research. It is intended to create awareness on how ageing factors influence crashworthiness of vehicle structure. As ageing study is a broad subject, this paper is focusing only on corrosion effects that lead to reduction of metal thickness of the structure, followed by deterioration of its mechanical properties. These effects are applied into finite element of bus structure. Rollover test according to UNECE standard (Regulation 66) is used to compare the performance of the original and aged conditions of the bus. For simplicity, this study uses the term 'bus' to represent all types of buses and coaches, except articulated and double deck.

2 UNECE Regulation No. 66

The aim of UNECE Regulation 66 is to make sure that defined safety space within the bus is well protected by the superstructure of the bus during and after the roll-over test. Safety space, or officially called as "residual space", is a space to be preserved in the passengers', crew and driver's compartment(s) to provide better survivability for passengers, driver and crew in case of a rollover accident [1]. This is shown in *Figure 1*.

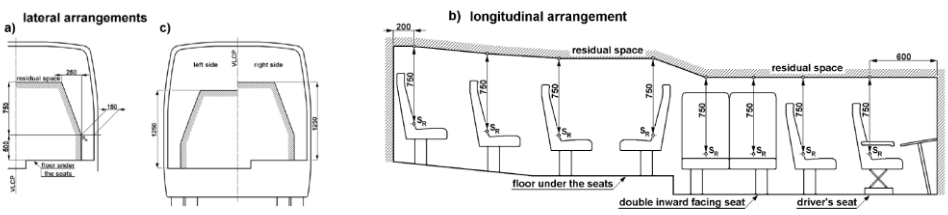


Figure 1: Lateral and longitudinal arrangement of the residual space in a bus [1]

"Superstructure" means the load-bearing components of the bodywork as defined by the manufacturer, containing those coherent parts and elements which contribute to the strength and energy absorption of the bodywork, and preserve the residual space in the rollover test [1]. Rollover test, as illustrated in *Figure 2*, is conducted to make sure the external parts of the bus like pillars, safety rings and luggage racks are not penetrating or intruding into the residual space. If this happens, then the test is considered fail.

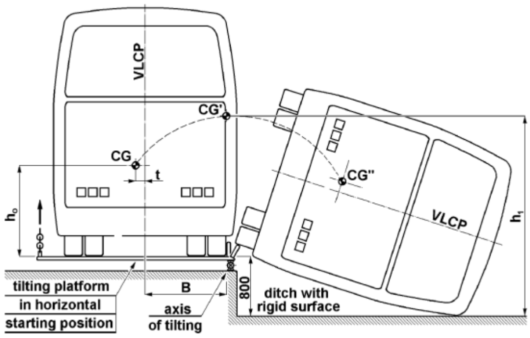


Figure 2: Full roll-over test [1]

The test is intended for the certification of newly designed bus. However, after the R66 certified bus has operated for a period of time, it is not known if the same bus can pass the same test again. This is because the bus has undergone service environment and service condition that may affects and deteriorates its crashworthiness performance. In other words, ageing factors may influence the strength of the bus superstructure.

3 Materials Ageing

The purpose of materials ageing study is to understand how the service environment and condition it is exposed to deteriorates its properties during its service life. By knowing this, its integrity can be determined and maintenance program can be applied to protect its safety and reliability.

3.1 Causes and Effects of Material Ageing

Material ageing phenomenon is the source of deterioration of bus structures. *Figure 3* summarizes factors contributing to its ageing. How much and how long ageing factors develop ageing effects are not in the scope of this paper. However these factors are introduced briefly in order to recognise the ageing causes and their effects on vehicle structural materials.

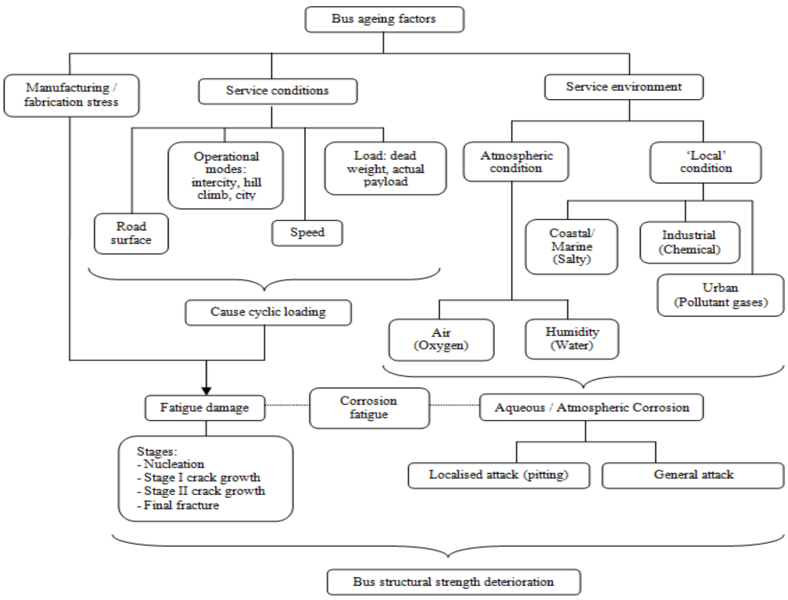


Figure 3: Ageing causes and effects leading to bus structural strength deterioration [2]

3.2 Case Studies on Aged Buses

Buses in Malaysia operates sometimes up to 30 years, and few are even beyond that [3]. By analysing the corrosion effects on aged buses, it can be seen that most of the structural parts are badly corroded and some are deteriorated to nearly zero thickness. For this study, it is within the practical boundary to consider the worst corrosion damage that can possibly occur on the bus. This gives the minimum possible thicknesses percentage of bus structure.

Few investigated cases are selected to support the argument as shown in *Figure 4(a)* to *4(c)*. Corrosions are marked in red circles. In *Figure 4(a)*, the upper frames are experiencing fairly moderate level of corrosion. While in Figure *4(b)*, side steel structures are badly rusted and few elements have zero thicknesses. These corrosion damages are considerably less compared to *Figure 4(c)* where the lower frames are totally rusted and have zero thicknesses for some of them. It is reasonable to believe that the other surviving areas of these lower frames are deteriorated very severely as well and the remaining thickness are significantly reduced.

(a), Case [4] *(b), Case* [5] *(c), Case* [5]

Figure 4: Different level of corrosion severity at (a)upper, (b)side and (c)lower frame of the bus

3.3 Estimation of Ageing Effects

Atmospheric corrosion is one of the major ageing effects on structural steels. In general, if the steels are not protected properly, corrosion develops gradually through time. *Figure 5* shows that coating protects the steel for some time. After the end of the coating lifespan and transition period, corrosion damage starts to develop. The concave and convex curve representing acceleration or deceleration of corrosion rate, respectively. A linear approximation is often used to simplify the analysis.

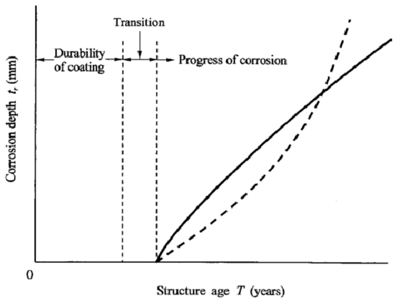


Figure 5: Stages of corrosion process [6]

Figure 6 [7] shows good examples on how yield strength and ultimate tensile strength of corroded steels degraded when it is under cycles of accelerated ageing test. It means that for steels exposed to continuous corrosion damage, mechanical properties are damaging as well. The degradation of mechanical properties of the steels is partly due to the reduction in cross-section and partly due to the increase in surface roughness.

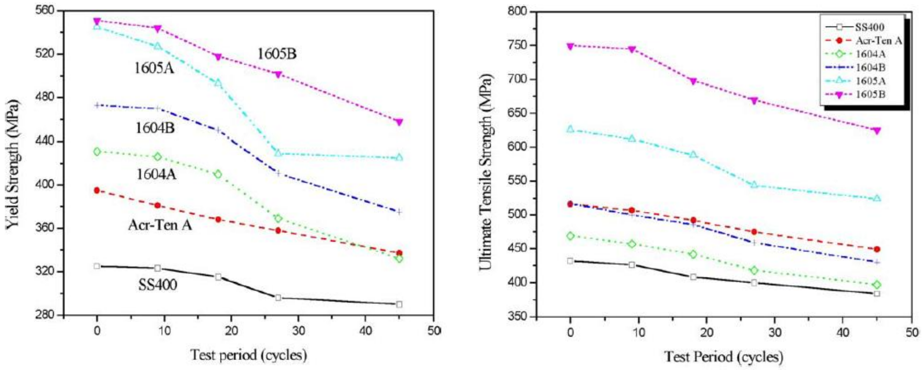


Figure 6: Deterioration of yield strength and ultimate tensile strength against test cycles, [7]

The relationship between corrosion severity and mechanical properties deterioration is illustrated in ratio in *Figure 7*. Basically it shows how mechanical strength of the steels decrease when the level of corrosion becomes worse [8].

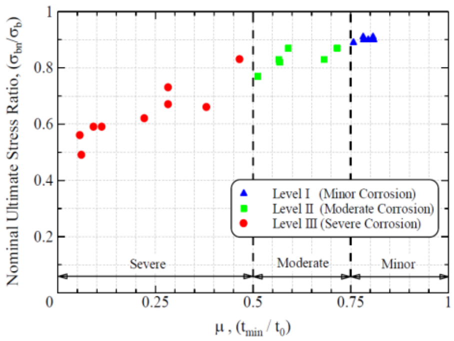


Figure 7: Nominal Ultimate stress Ratio vs. thickness ratio [8]

With the consideration of the available data presented above and their suitability for this study, the following practical assumptions are made:

1. The maintenance program of the bus (e.g. periodic maintenance on corrosion protection) is poor, and therefore, the corrosion starts immediately after the expiry of coating durability and transition period.
2. Since the lower frame of the bus is exposed to corrosion environment (e.g. contact with water and chemical substance) more than other parts of the bus, it becomes the most corroded section. This is followed by side frame, and lastly the upper frame. Thus the level of corrosion of the bus can be generally divided into 3: very severe (for lower frame), severe (for side frame) and lightly severe (for upper frame).
3. Bus skin, like the lower part, experiences the worst corrosion. It is noted that bus skin contributes towards the overall superstructure strength, as mentioned in [9].
4. For atmospheric corrosion study, it can be divided into general and localised (pitting) types. It is assumed that general corrosion uniformly affects the bus structure and its skin. Localised corrosion can be inserted in a random fashion with its percentage varies from one part to another. It is practical to insert its value if the elements are small, for example four or eight elements per surface width of the square tube. But this requires a large number of elements which may reach up to 500 thousand elements. As this study only use one element per surface width of the square tube and the total elements of less than 150 thousand, insertion of localised corrosion is almost impossible and impractical, and thus will not be considered.

Thus, for the current study, it is reasonable to set input data as follows to simulate the worst possible ageing condition of the bus:

1. It is assumed that the remaining thickness of structural parts of the bus is 30% for upper frame, 20% for side frame and 10% for lower frame, of the original. The bus skin and minor

non-structural parts that are mostly located near the lower area of the bus are assumed to have remaining thickness of 10% of the original.

2. By extrapolating the relationship between mechanical properties deterioration and steel thickness reduction as in *Figure 7*, remaining yield stress is 70% for upper frame, 65% for side frame and 60% for lower frame, bus skin and non-structural parts.
3. Major parts like engine, drive shaft and gear box maintain their original properties.
4. Welded joints of structures are assumed to remain intact and maintain its original properties.

4 Finite Element Model

The finite element bus model used for this study is taken from free domain, finite element model archive [8]. It is a model of CONTRAST bus, a single deck high-floor bus for district use (intercity bus) assembled by VEST-BUSSCAR Company.

4.1 FE Model: New bus condition

Residual space envelope (in red) was created in the bus according to specifications mentioned in Regulation 66 shown in *Figure 11* (Section 2). This was for viewing purposes only, so this space was assigned with material MAT_RIGID with no contact definition with other parts. To make sure it will not be displaced from its position during rollover, it was attached to the floor parts, as floor will not get deformed in a rollover.

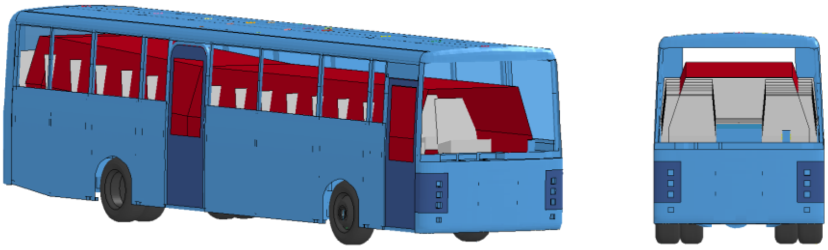


Figure 8: Residual space envelope (in red)

During simulation of an aged bus, error occurs on bus seats. To eliminate the error, it was decided not to include bus seats in the analysis, leading to a reduction of 1.4162 tonne. This changes the overall weight from 12.986 tonne to 11.570 tonne. The bus started to rollover when the platform tilted at 49^{o}, (*Figure 9(a)*), crashed on the rigid wall (ground) and reached its stability position at t=7 second (*Figure 9(b)*).

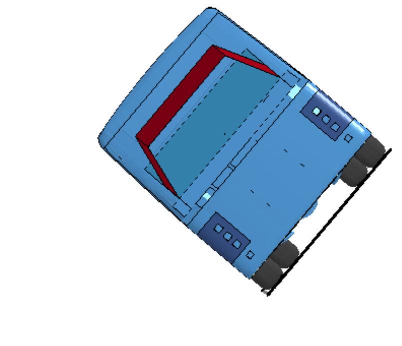


Figure 9(a): Rollover started at 49 degrees.

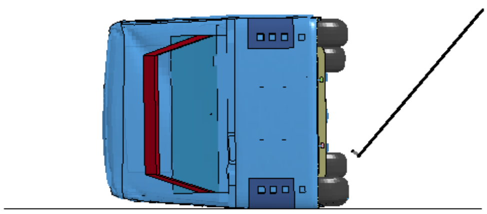
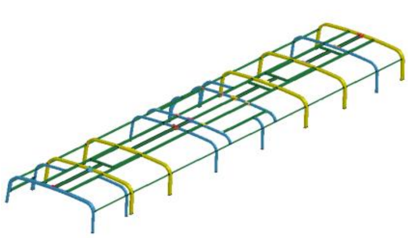


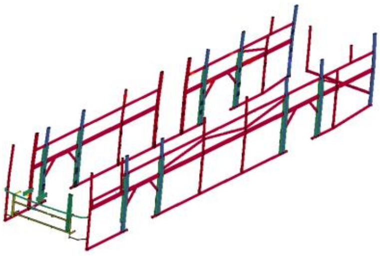
Figure 9(b): Final position of the bus

4.2 FE Model: Aged bus condition

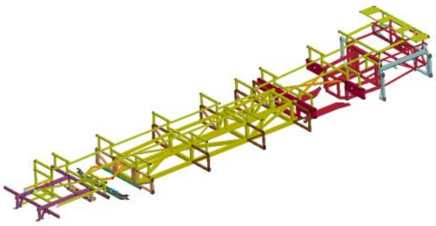
The same procedure used for new bus was used for aged bus. Percentage of deterioration of structural thickness and yield stress reduction are applied to the upper frames, side frames and lower frames as shown in *Figure 10(a)* to *10(d).*



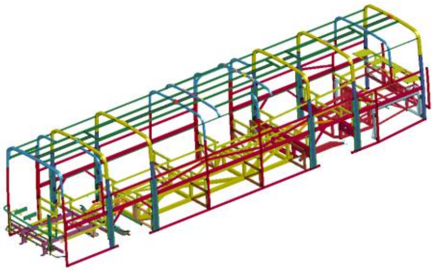
(a): Bus upper frame



(b): Bus side frame



(c): Bus lower frame



(d): Overall bus frame

5 Rollover results and discussion

5.1 Finite Element Rollover Test

Figure 11(a) shows the condition of a new bus after rolled over. The overall structure is generally remained intact and residual space envelope is not penetrated, so it passed the test. *Figure 11(b)* shows the condition of aged bus after rolled over, whereby the upper structures are clearly penetrating the residual space. Hence the test for the aged bus is obviously failed.

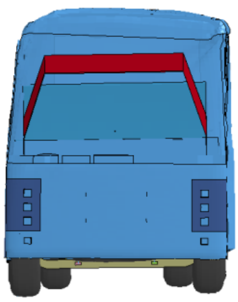


Figure 11(a): New bus condition after rollover

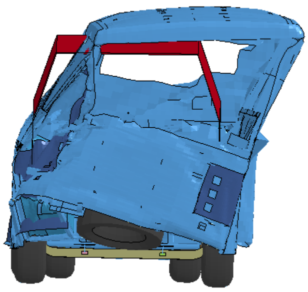


Figure 11(b): Aged bus condition after rollover

5.2 Case studies of real world rollover of aged buses

From real-world crash investigation of bus roll-over in Malaysia, it can be seen that there are some degree of similarities of structural deformation between real-world roll-over crash and simulation. This can be observed in *Figure 12(a)* and Figure *12(b)*. The superstructure condition in *Figure 12(b)* which the service age is 20 years is worse than that in *Figure 12(a),* which the service age is 4 years.

However, real world are totally different because laboratory and numerical variables are properly and strictly controlled. The severity of the crashes depends on many factors. Some of it are different crash conditions like velocity before impact, crash configuration, weight of the bus, design specification, compliance to safety standard requirements and maintenance management, while this study is only focusing on ageing factors.

Figure 12(a): Service age is 4 years [11]

Figure 12(b): Service age is 20 years [12]

In [13], number of fatality per each bus crash case is plotted against service age of the bus, as in *Figure 13*. The methodology to obtain this statistics will not be discussed here. Generally, it can be observed that there exists relationship between increase of fatality number in a crash with the increase of bus service age.

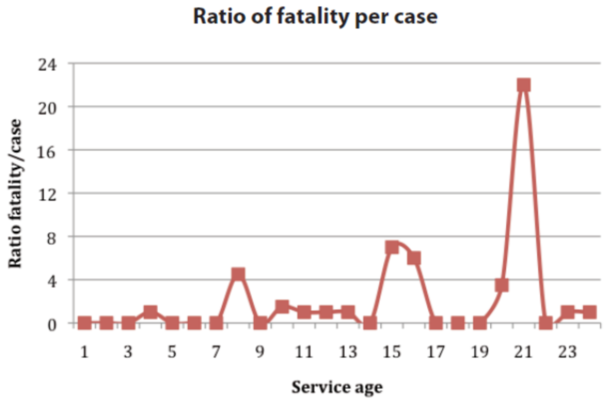


Figure 13: Ratio fatality/case vs. service age

6 Conclusions and Future Works

Ageing effects such as corrosion damage and consequently the deterioration of mechanical properties of bus steel superstructure, influence the crashworthiness performance of the bus. The performance is expected to be worse if other ageing effect like fatigue is considered. Future works will include the estimation of ageing rate based on input variables from service environment and service condition of the vehicle. This preliminary study can be developed further to establish a new assessment method for the evaluation of crashworthiness level of aged vehicle.

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3. Bus model creator, Pezzuchi Matteo, for permission on using its latest Contrast bus FE model

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