New Fatigue Life and Durability Evaluating Method of High Speed Train Carbody Structure

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Abstract With the development of new generations of CRH trains in China, one new fatigue integrated analysis method was proposed to evaluate high speed train carbody structure fatigue life and durability. The CRH train's carbody structure was used here as an example for study the interaction relation between vehicle dynamic characteristic and fatigue property running in BEIJING-TIANJIN intercity line. The detail method steps include: Firstly, MBS (Multi Body Simulation) technologies allowed the development of more detailed and accurate vehicle-rail rigid-flexible coupled dynamics model which can be used as input of stress distribution calculation. And The typical carbody structure's fatigue load spectrum and extrapolation were calculated here through quasi-static stress method according to field running condition for different radius curve (400-2500 m), which was random combination of Track irregularity, W/R profile and Cant deficiency. Secondly, Aluminum alloy structure FE (Finite Element) analysis technologies, such as modal analysis, substructure and stress calculation, were used to determine structure critical location and understand carbody structure nature frequencies and mode shapes influence. FM (Fracture Mechanics) assessment analysis for different load condition combination based on the structure stress distribution and stress/strain time histories results. Thirdly, carbody structure fatigue stress distributions in carbody selected dangerous regions were calculated in sub-model. And The analysis results were compared with the field dynamic stress test results. Finally, carbody fatigue life and durability analysis results were estimated based on aluminum material S-N curve with Palmgren-Miner damage cumulative theory. The critical structure fatigue failure influence can be taken into account in stress distribution used as input of FM. This work targets the capabilities of MBS and FEM (Finite Element Method) in the fatigue and durability design early stage and verification phase of the high speed train key structure, such as bogie structure, axle and wheel, etc. The results also illustrate that the proposed numerical simulation method can give an important contribution in terms of high speed train key structure component fatigue and durability evaluation.

Keywords Railway, Carbody, Fatigue life, Multibody Dynamics, FEM

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1. Introduction

With the rapid development of high-speed railway in China, the CRH series train's vehicle key structure components fatigue design and analysis method are also facing the serious challenge of many technical difficult problems, such as running safety and ride comfort. Especially for the important structural components fatigue design and durability analysis method, there are many aspects worthy of consideration and study [1-2]. Despite the conventional railway vehicle structure fatigue design method had been applied in some structural components' durability during last years .But with the continuous improvement of vehicle speed, it has been revealed that dynamically loaded structure components' fatigue damage and structure destruction maybe become one of potential technical problems in future. Most of the recent research on the dynamic behaviors of vehicles /rail has been simulated by the need to understand the basically cause of practical service problems arising from the interaction between the vehicle and the track and to develop solutions or treatments for those problems.

With respect to structural fatigue problems, great deals of research have been done these years. During the more recent structure fatigue simulation techniques research, an integrated design methodology had been made use to evaluate structural fatigue (R.K.Luo,et al.1994, Stefan Dietz,1998).These procedures make use of multibody simulation packages (Schielen, 1990;kortum and sharp,1993) to determine the dynamic loads acting through the suspension onto the vehicle structure. Measured track data are generally used as excitation inputs. Using a finite element model of the structural a component on which the dynamic forces are acting, stress concentration locations are identified and analyzed. Structure dynamic stress histories are determined under simulated loading and the fatigue life is determined using an appropriate fatigue theory. In reference [3], the author had systematically presented one hybrid simulation method to the carbody structure fatigue life assessment based on **MBS** (Multibody Simulation) and **FEM** (finite element method). In this paper, based on some typical literatures' achievements [4-7], one new fatigue life and durability evaluating method of high speed train carbody structure is proposed here to evaluate the carbody structure fatigue property and applied to the structure fatigue design. And one complex railway EMU carbody was used as an example to describe the detail method steps how to use in fatigue design development processes.

2. Structure Fatigue Numerical Calculation Method

There are three main factors, which affect the structure fatigue behavior: The S-N curve of structural components; the load time histories; and structural geometrical features. The carbody structure of railway vehicle is subjected to a very large number of variable amplitude stress cycles during their operational life. Large structural stress and complex load conditions are the main causes which lead to vehicle structural components' fatigue crack initiation and crack growth. And the weld structure manufacturing process of the structural components is one of the main factors which cause the structure destruction. Since this paper focuses on the structural fatigue damage caused by vehicle structural dynamic characteristics, so there will not be to evaluate the structure damage from the perspective of welded structural fatigue. Some weaknesses locations of the carbody structure are studied, such as the location of the secondary suspension, the traction or braking, the corners of the window, and so on.

This method considers the dynamic behavior of the full vehicle. It can greatly reduce the physical prototype test cost and design fault, while it can improve the accuracy of structural durability design and life prediction. Fatigue is one of the primary mechanisms causing deterioration of high speed train vehicle carbody structure during its lifetime. Straight track, tracking/ braking, curve passing, aerodynamics effect and other cyclic or alternating loads easily subject the carbody structure to huge numbers repeated stress over its life time. Cyclic loading causes fatigue cracks initiation, which causes cracks to form in the structure. These cracks grow longer with each stress cycle, degrading the carbody's structural strength and life. A crack initially grows slowly, but the rate accelerates as these cycles accumulate, to the point at which rapid crack growth results in a fracture. Thus, some durability design criteria for carbody are those can endure accumulated fatigue damage during service Life-Cycle to prevent structural failure.

A full vehicle's multibody dynamic model including carbody, bogies, the primary suspension and track are set up using the famous MBS software pack SIMPACK. The vehicle is described as rigid bodies interconnected via several different suspension systems. Several typical load cases, such as tangent line and curve passing, were performed in order to verify the accuracy of the dynamical model in reproducing the full vehicle dynamic behavior simulation. Carbody structure fatigue analysis puts a great demand on accuracy including MBS and FEM model .The quasi-static stress method was performed for carbody to obtain the stress histories. FEM model cannot be too complex since the dynamic analysis and fatigue assessment is time consuming. The finite element analysis method was used in software ANSYS. The load time histories are very important aspects since they are the actual source of fatigue failure prediction. Several complex loading conditions must be determined, either by analytical approaches or by dynamic stress tests. Due to the computational effort involved in dynamic simulations, only selections from the stress history can be used. Decisions as to what loads to apply must therefore be designed and selected analytically. Different types of railway vehicle operational conditions must be considered in additional to some extreme load cases generated from error operation.

A fatigue assessment method describes a sequence of steps to be taken in order to predict fatigue life from a given state of stress and strain. For carbody subjected to variable amplitude stochastic loading, the main steps include:

- Rain flow cycle counting;
- Damage calculation for each cycle;
- Fatigue damage accumulation.

The proposed new method for high speed train carbody structure is shown in Fig.1.

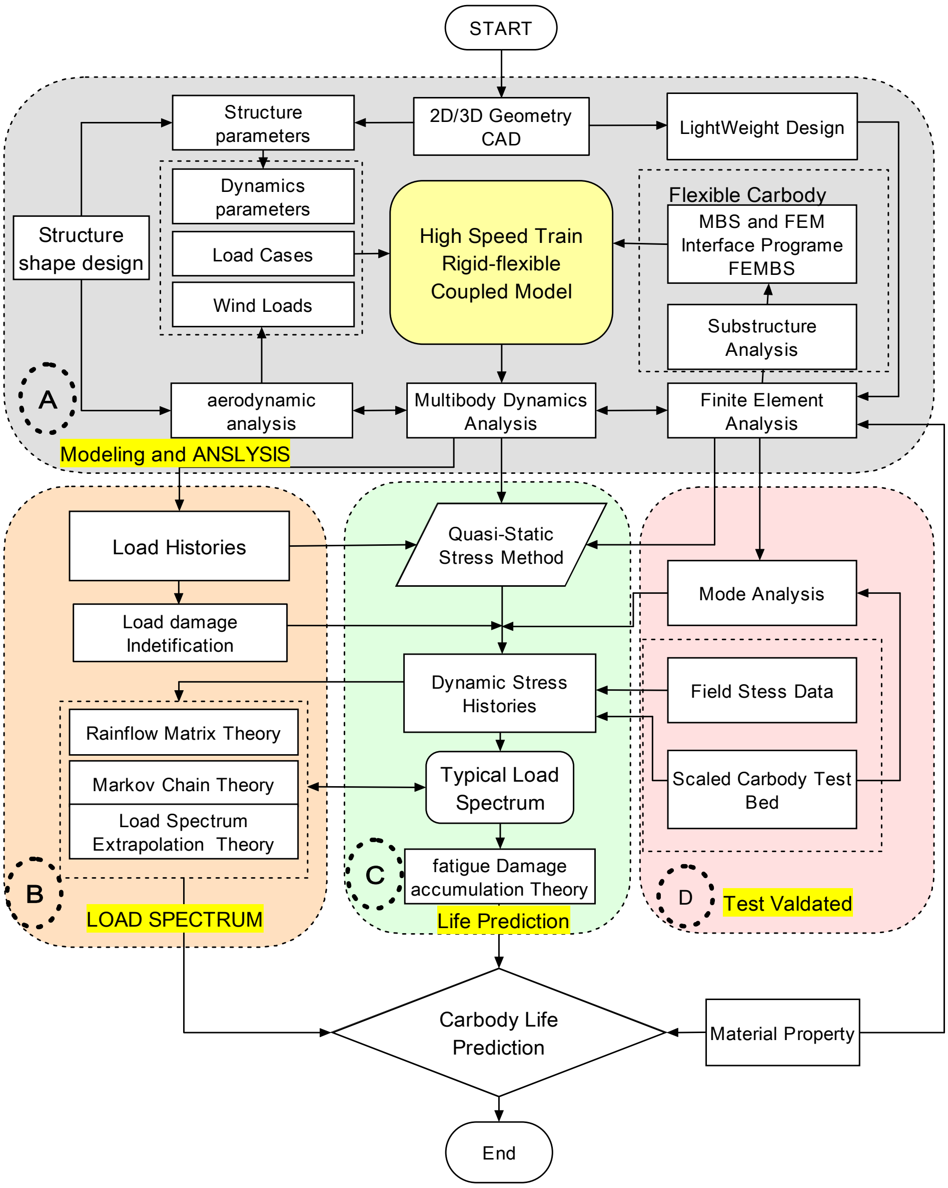

Fig. 1: New carbody structure fatigue life evaluation flowchart

Vehicle Dynamics Simulation with MBS. Dynamics analysis of the full vehicle can be used to obtain the load time histories for the carbody structure in typical running cases, such as the straight and curve lines. The CRH train vehicle was selected for this study to create the detailed multibody dynamics model, which was running between the Beijing-Tianjin intercity lines in China. The model has been substantially altered to accommodate more load cases and used to simulate railway vehicle dynamic behavior. The loads such as inertial loads and external loads derived using multibody dynamics analytical methods are mostly used for fatigue calculation [8].

The vehicle has been modelled with the aid of the MBS software SIMPACK library elements like rigid or flexible bodies, force elements and joints. The carbody was described as rigid body by each other. Several linear spring and damper elements describe the primary and secondary suspension unites, the bump stops and viscous dampers are represented by nonlinear characteristics. The configuration and suspension characteristics of the system are included in the dynamic model. The full vehicle multibody dynamics model was shown in Fig.2.

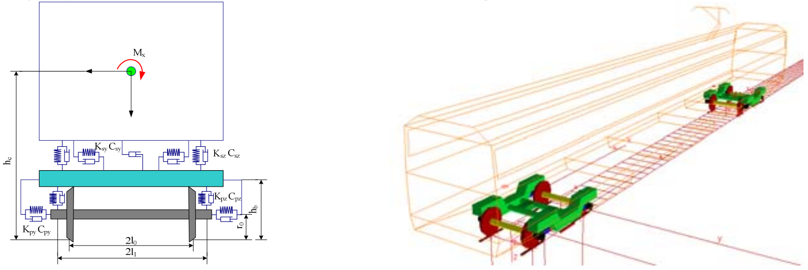

Fig.2: Dynamic model of carbody

The typical running case in operating condition has been designed to perform multibody dynamics simulation, which includes straight running, curve passing and traction/braking etc. The load histories have been calculated in MBS, which include forces, velocities, accelerate and angular velocities etc. And in order to take account of the influence of elastic carbody, the interface program FEMBS between finite element analysis codes and SIMPACK is used here to generate input data for flexible bodies to MBS simulation. The paper adopted the track irregularities is the real track excitation spectrum. They run on a straight railway in speed 200 km/h to 300km/h. Some dynamics simulation results are shown in Fig.3.

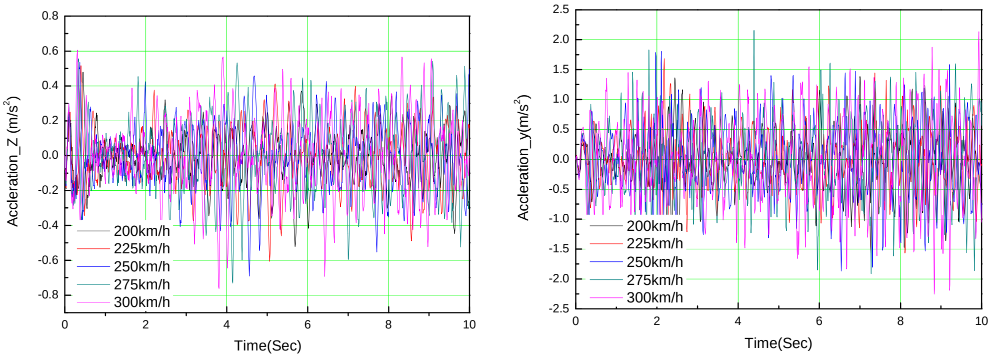

Fig.3: Vertical and lateral acceleration of carbody center

Finite Element Modeling of Carbody. The carbody structure fatigue damage is mainly caused by the vehicle dynamic response, which is usually expressed as stress or strain time history. Stress/Strain calculations for fatigue life estimation can be performed in the time domain or frequency domain. The quasi-static stress method was used to obtain the stress/strain time histories. The detail carbody stress analyses with ANSYS were performed based on MBS and FEM. And mode analysis is also performed here. The finite element model of the carbody is shown in Fig.4. Modal analysis is usually used to determine the natural frequencies and mode shapes of carbody structure. The modal analysis results are shown in Fig.5 and Table1.

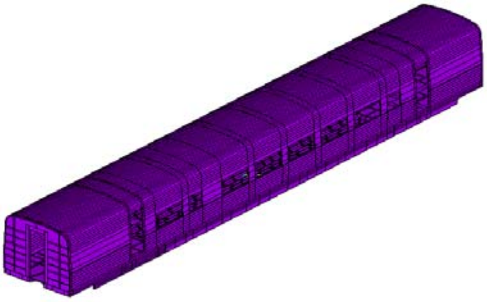

Fig.4: Carbody finite element model

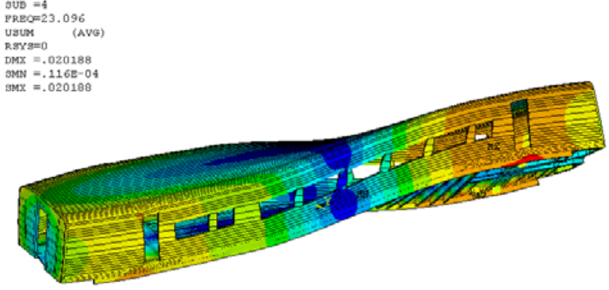

Fig.5: The 1st Torsion mode of Carbody structure

Table1.The results of the modal analysis

Mode No.	Frequency(Hz)	Mode shape
1	13.186	1st Lateral bending
2	19.078	1st Vertical bending
3	21.700	2ndLateral bending
4	23.096	1st Torsion
5	23.438	2nd Vertical bending
6	25.627	3rd Lateral bending
7	26.836	3rd Vertical bending
8	30.477	2nd Torsion
9	30.779	4th Vertical bending +Breathing
10	33.762	Breathing

Fatigue Assessment of the Carbody Structure. The carbody structure fatigue life was predicted. and compared with the life calculated from the original test datum. The material used in the carbody was A6N01S-T5.The stress-Life(S-N) curve was created in software *Fe-Fatigue* according to the material fatigue design manual which is used in the fatigue life calculation. Based on the structure *S-N* curve and the Palmgren-Miner rule, the carbody structure fatigue life was evaluated. The results of the rain flow cycle counting are usually presented as a rain flow matrix giving the number of cycles occurring at various combinations of range and mean stress [9, 10]. Then the values of range and mean are rounded off to discrete values to give a matrix of manageable size. The calculation results for test point and node 70770 corresponded to the test points are shown in Fig.6.

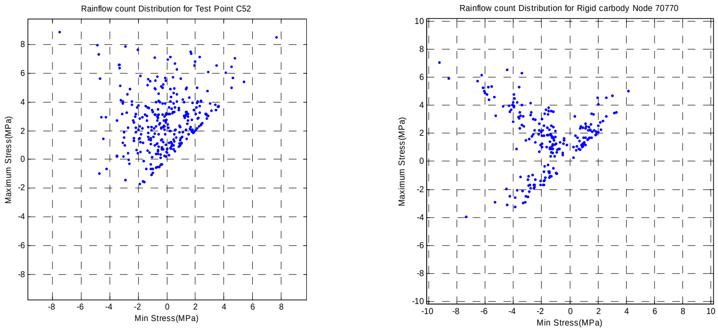

Fig. 6: Rainflow cycle count of C52 and Node 70770

3. Field Lines Dynamic Stress Test

In order to determine the accuracy of strain predicted from the simulation model, the field lines dynamic stress/strain test for carbody was performed to the carbody fatigue estimation. And fatigue life of carbody was calculated from the original field dynamic stress test data. The field dynamic stress/strain test points for the carbody and results for test point C52 are shown in Fig. 7.

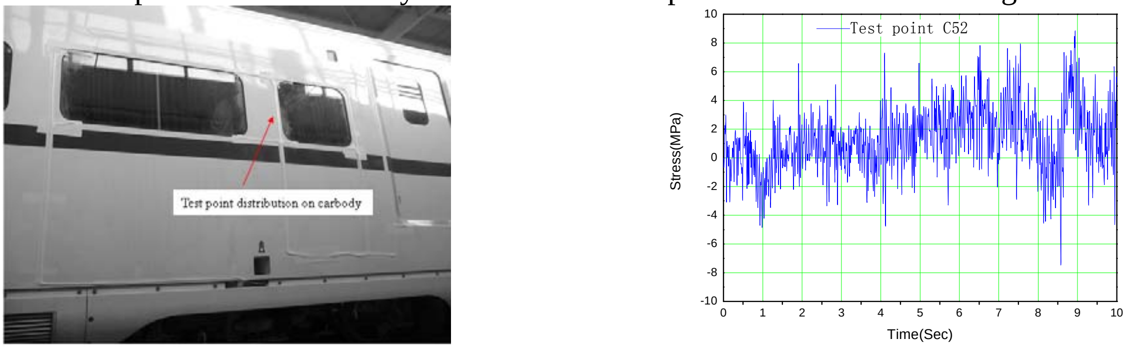

Fig.7 Dynamic stress/strain test and results for carbody

4. Results and Discussion

The primary goal of this paper is shown how to correctly evaluate the railway structure fatigue damage at the critical location of the carbody. It can show the relation mechanism between full vehicle's carbody dynamic characteristic and structure fatigue property. The safety factor analysis based on *S-N* method based stress was used to calculate the carbody damage distribution. Finally, according to rain flow matrix and Markov chain theory, material *S-N* curve, structure dynamic stress, and Palmgren-Miner damage summary theory, carbody structure fatigue life can be evaluated and compared with the field stress test results. Some carbody structure fatigue life calculation results are shown in Table2.And some fatigue analysis results are shown in Fig. 8.

Table 2. Fatigue life estimation comparison

Name	**Mean**(MPa)	**Min** (Mpa)	**Max**(Mpa)	**Range**(Mpa)	**Life repeats**
Test point c52	1.436	-5.814	9.522	15.336	2.694e6
Node 70774	-0.903	-9.253	7.045	16.298	2.278e6

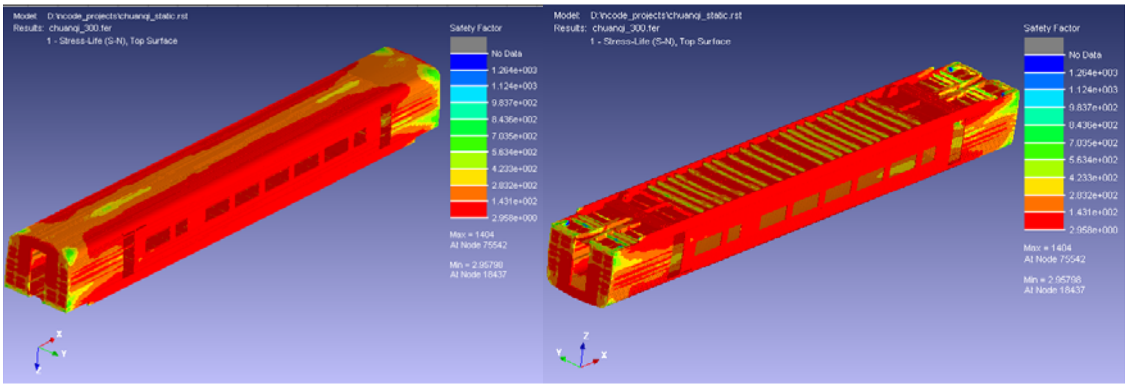

Fig.8: Safety factor analysis results

5. Conclusion

The new fatigue life and durability evaluating method of high speed train carbody structure based on MBS and FEM was proposed to evaluate the CRH vehicle carbody structure fatigue properties. This method can be used in early structure fatigue design in railway carbody structure new product development stage. Some simulation results are also shown and compared with the field dynamic stress test results to validate the method effective. The results also prove that the MBS-FEM simulation method can evaluate the carbody structure correctly. It is also beneficial to understand the influence for dynamic property to structure fatigue life prediction and satisfy with railway key structure component's durability design.

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