

NUMERICAL STATIC AND DYNAMIC STRESS ANALYSIS ON RAILWAY PASSENGER AND FREIGHT CAR MODELS

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Abstract

Railway vehicle structures generally consist of shells, plates and beams, and behavior of these members directly affects static and dynamic structural behaviors of these vehicles. In this study, numerical results on stress, vibration and crash analyses of railway passenger and freight car structures made of steel members are presented. Finite element (FE) method is used to assess the static and dynamic structural behavior of railway vehicles. Full length detailed railway vehicle models are used in all FE analyses. FE models should be validated against experimental measurements; most common-base references that are taken into account are UIC CODE OR 577 and ERRI B12/RP17. As a result of relevant simulations, static and dynamic structural characteristics and structural weaknesses of designs are determined. Suggestions for improving dynamic, static and crashworthiness characteristics of rail car structures can be proposed.

Key words: Railway vehicles, structural analysis, crashworthiness, finite element methods.

1. Introduction

Before putting a railway vehicle into service, it must be certified. Static and dynamic tests are performed according to international standards during the certification procedures. Some standards, specifications and requirements for static stress tests, vibration and crashworthiness of rail vehicle structures can be found [1- 6]. Numerical methods and experimental measurements are used to determine static and dynamics behavior of railway vehicles. Experimental measurements are very time consuming, expensive and they cannot be used at all stages of design. Hence, today numerical methods are important tools in static and dynamic analyses of railway vehicles. Although numerical simulations do not have aforementioned disadvantages of experimental methods, they must be verified by experiments to obtain realistic results. FE method is a powerful numerical engineering analysis tool, and widely used in static and dynamic stress analyses of railway vehicles [7-22]. Although, design phase by using the FE analysis of the railway vehicle models take certain time, it can be used easily for a number of cases such as different crash scenarios with different speeds and all stages of design and improvement by using its economy and flexibility.

Static structural, vibrational, crashworthiness and optimization studies of railway vehicles should be performed to provide optimum safety, comfort and energy saving. Full-length, half- width / full-length and half-width/half-length modeling approaches are used to determine static structural, vibrational and crash behaviors of railway vehicles depending on the symmetry of vehicle. Nevertheless, half- width / full-length and half-width/half-length modeling approaches can be used only for certain types of simple static structural loading such as static symmetrical compression and symmetrical tension loading conditions and cannot be validated for complex static structural loading and dynamic loading conditions. Hence, full-length simulations are important for the validation of designs and to provide the greatest possible accuracy [13]. To obtain static structural behavior of the railway vehicles, i.e., stress and strain distribution, different static loading cases defined in standards such as UIC CODE OR 577 and ERRI B12/RP17 [5, 6] can be used in FE analyses [19- 21]. The natural frequencies and elastic mode shapes of railway vehicles, which represent its vibrational characteristics, can be obtained by using FE methods [16- 18]. To obtain crashworthiness characteristic of railway vehicles, different crash scenarios can be evaluated by using FE methods [7- 16]. Most of the analytical studies on the crash characteristics of railway vehicles simulate a collision into a rigid wall [7, 8, 11]. This is an ideal and simple approach to reveal the general crash characteristics of full-scale railway vehicle models. Different types of crash simulation scenarios can also be found in literature [12, 22].

In this paper, considering the above mentioned issues, analyses of stress, vibration and/or crashworthiness of railway passenger and freight car structures are completed. Full-length detailed and validated FE models are used to assess static, vibrational and dynamic structural behaviors of the railway vehicles. To obtain static structural behavior of the railway vehicles, different static loading cases defined in standards are used. To obtain vibrational behavior of vehicles normal mode (free vibration) analyses are performed. Crash behavior of the passenger car is assessed by studying the impact of a single vehicle with a rigid wall [14,15]. Impact speed of 90 km/h (25 m/s) is chosen in studies and better crashworthiness properties are obtained by using size optimization [14]. As a result of all simulations, structural weaknesses and suggestions for improving

static and dynamic structural characteristic of the structural designs are determined. Crash analysis of freight car is also assessed by studying the impact of a single car into a rigid wall at the impact speed of 30 km/h.

2. Numerical static and dynamic stress analysis on railway passenger and freight car models

2.1 Railway passenger and freight car models

Railway passenger and freight cars called respectively “N13-type” and “SGS-type” used by Turkish State Railways are examined in this study. The passenger car body is mainly made of 5 different steel materials (i.e., stainless steel, St 12, Stw 24, St 37 and St 52), composed of two sidewalls, underframe, roof frame and two end walls while freight car is mainly made of St 52 and composed only underframe. Most of the structural components of the railway passenger and freight cars are made of shells, plates and beams. While the railway passenger car has 11 different thickness values of structural components and freight car has 8 different thickness values of structural components.

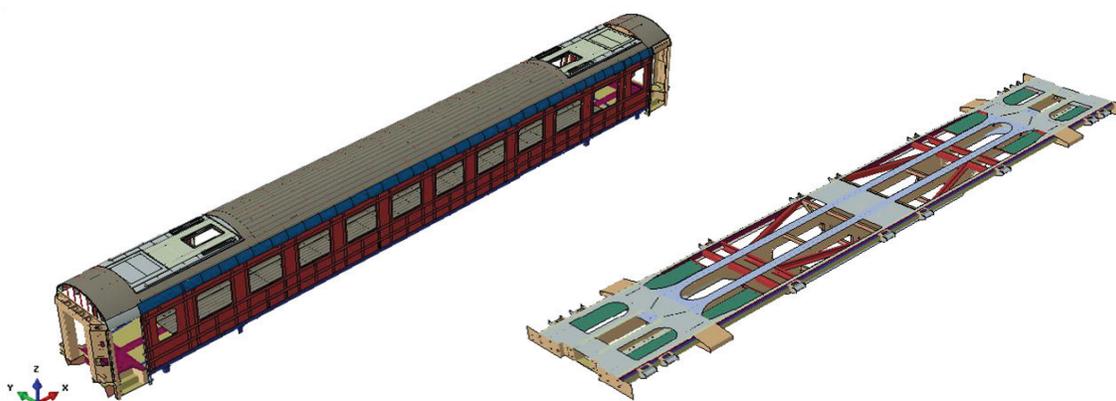


Figure 1 FE models of railway passenger and freight cars.

Full-length detailed car models are used to obtain more realistic results. Figure 1 shows the FE models of railway passenger and freight cars. Bogies, auxiliary equipments, passengers and the rails have not been modeled explicitly in models but the corresponding point masses and appropriate boundary conditions were considered in crash and static analyses. The railway passenger and freight car models have approximately 2,000 and 330 different components, respectively. Table 1 shows the dimensions of railway passenger and freight cars used in this study. The weight of the passenger and freight car bodies are respectively approximately 25 tons and 14 tons including the total weight of the two bogies.

Table 1 Dimensions and weights of the railway passenger and freight cars.

Model	Length (mm)	Width (mm)	Weight (tons)
Passenger car	26000	2800	24
Freight car	13700	2720	14

To obtain the best balanced accuracy and efficiency in numerical simulations, standard convergence test are applied. By using different mesh refinement levels, stresses in the critical regions are computed and an acceptable mesh level is considered. Table 2 shows total numbers of elements and nodes of the railway passenger and freight cars in the final FE models. Both models mainly consist of first order quadrilateral shell elements. In addition, 44,346 rigid connection elements are used to represent weldings in passenger car FE model.

Table 2 Total numbers of elements and nodes of the cars in FE mesh.

Model	Total elements	Total nodes
Passenger car	1656900	1682540
Freight car	892132	892770

2.2 Static analysis of the railway passenger and freight car models

To obtain static structural characteristics of the railway passenger and freight car structures, UIC CODE OR 577 and ERRI B12/RP17 standards are used. Railway vehicles are subjected to different loading scenarios in these standards such as symmetrical compression force and tensile force. According to these standards, loading and boundary conditions are adapted to FE simulations. To validate the FEM model, the same tests are also been applied to railway passenger and freight car prototypes (i.e., Figure 2). Strain gauge rosettes are applied to a quarter of the car bodies to capture the plane-stress behavior of the structures, and the simulation results are compared with experimental measurements. The strain gauges are located on the passenger car bodies based on FE results based on which critical areas in terms of stress concentrations are selected (i.e., Figure 2). To simulate the effects of luggage of passengers, passengers and container themselves, the floor of the car body is loaded by using sandbags.



Figure 2 Experimental setup and some strain gauges.

Figure 3 shows the comparisons between the simulation results and stress results calculated by using strain measurements at thirty gauge points. The results show that passenger car FE model is in good agreement with experimental strain gage measurements. Other experimental measurement and numerical simulation results also are also in good agreement for both passenger and freight cars and they are not presented here for limited space.

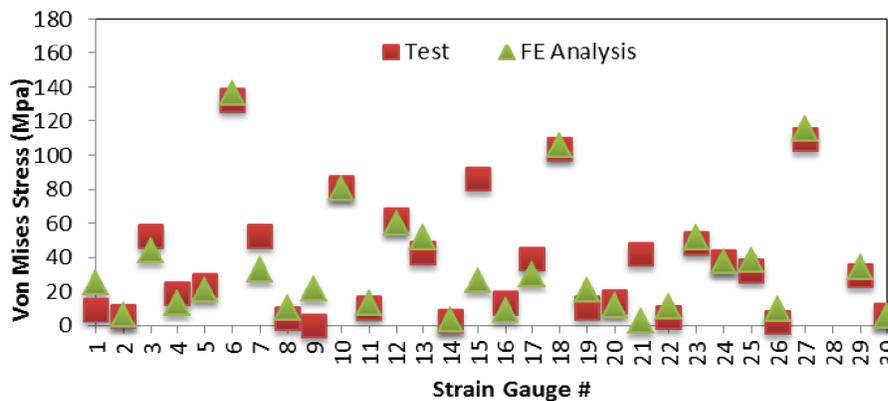


Figure 3 Results of symmetric compression force of total 200 tons with the loading of 29.66 tons for passenger car.

Figure 4 shows Von Mises stress contour plots of the tensile force of 100 tons for freight car and total 200 tons symmetrical compression force for passenger car where the railway vehicles are empty. In addition, displacement results obtained in the middle point of the passenger car body by using experimental measurements agree well with FE results (i.e., see Figure 5).

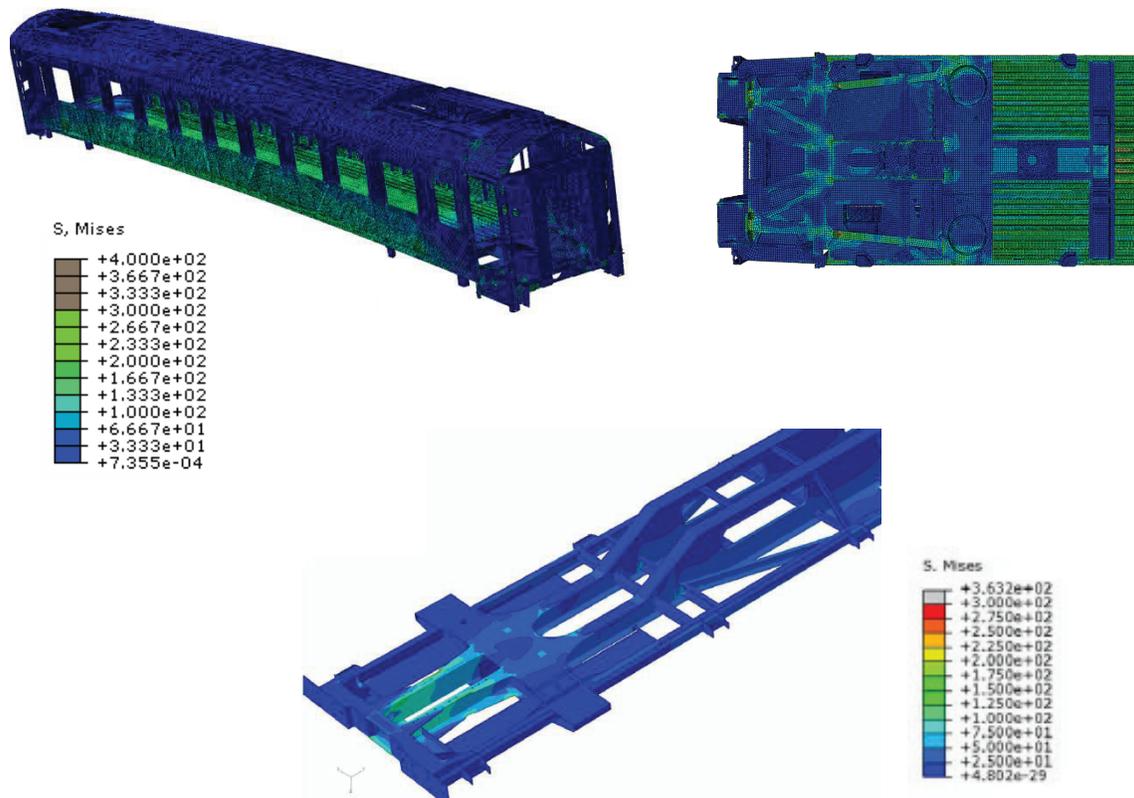


Figure 4 Von Mises stress contour plots obtained by total 200 tons of symmetrical compression force for empty passenger car (above) and the tensile force of 100 tons applied to empty freight car (below).

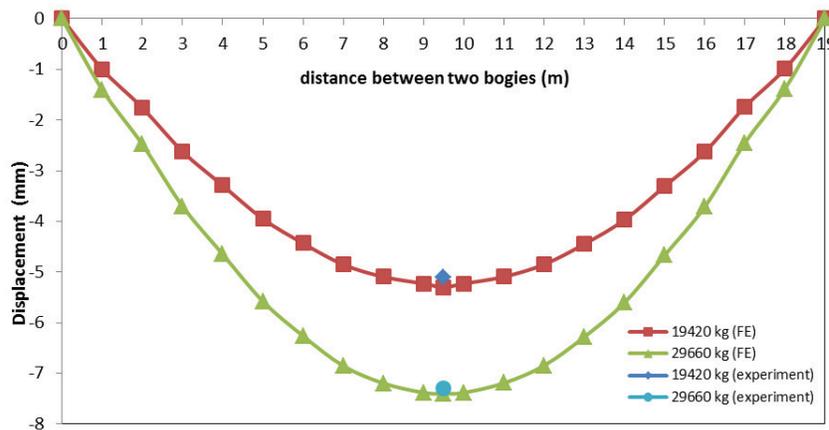


Figure 5 Displacement result of passenger car body loaded 19420 kg and 29660 kg.

2.3 Vibration analysis of the railway passenger and freight car models

With the growing use of advanced structures for the vehicle design, determination of the structural dynamics characteristics of vehicles is becoming increasingly important. The elastic mode shapes and modal frequencies of a railroad car, which represent its dynamics characteristics, can be evaluated by using computational methods. To this end, natural frequencies and mode shapes of the passenger and freight car bodies are computed. To obtain vibrational behavior of vehicles, normal mode or free vibration analyses are performed. Table 3 shows the first three eigenfrequencies of the empty passenger and freight car models. First three elastic mode shapes of passenger car model such as diagonal distortion, body shell breathing and bending modes which are shown in Figure 6. The mode shape with the lowest frequency shows a diagonal distortion of the passenger car body structures. The passenger car body's side walls vibrate against each other in diagonal distortion mode. These mode shapes are in accordance with results of a metro vehicle's

modal analysis in literature [18, 23]. In addition, the mode shape with the lowest frequency shows torsion of the car freight body structures. At higher frequencies bending modes of the freight body exist. The first three elastic mode shapes of freight car model are shown in Figure 7.

Table 3. The first three fundamental frequencies of passenger and freight cars (in Hz).

Model	1	2	3
Passenger car	9.0	12.5	17.4
Freight car	5.0	18.3	20.6

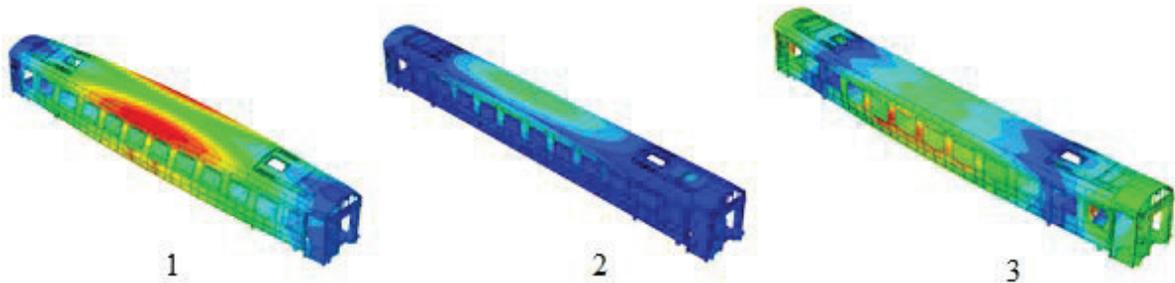


Figure 6 First three mode shapes of the passenger car body

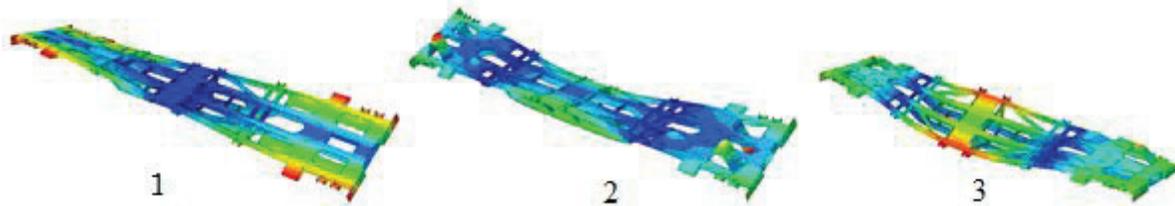


Figure 7 First three mode shapes of the freight car body

2.4 Crash analysis of the railway passenger and freight car models

The main aim of crash analysis is to provide optimum crashworthiness design and to prevent loss of life when impact occurs. Nowadays, passive protection design approach is used in rail vehicle design. According to this approach, when collision occurs, the rail vehicle should deform and collapse in a controlled manner in such way structural deformation progresses from the vehicle end to its interior, without damaging the passenger's living regions. Deformation of the railway vehicle progresses generally in five phase [24] as follows

- Shunting impact no damage,
- Energy absorbed in the coupler and buffers,
- Energy absorption after the deformation of the coupler and buffer,
- Progressive deformation of the end underframe,
- Passenger compartment deformation.

For the deformation to progress in a controlled manner it is necessary that deformation of structural members such as extruded beams and plates are also controlled as the amount of energy absorbed in a vehicle is directly related to the yield strength, work-hardening behavior, thickness and geometry of the structural members. Several crash scenarios are used to determine crashworthiness characteristic of railway vehicles such that, single-car impact with rigid wall, two-couples-car impact with rigid wall and rollover of vehicles. Rigid wall impact simulation is mostly used to reveal the general characteristics of impact behavior of car for its simplicity.

To investigate the damage in the passenger and freight cars, the impact speed of 90 km/h and 30 km/h are chosen. The impact behavior of the cars is assessed by simulating the crash of the car into a rigid wall. Following some impact simulations, the duration of collision is selected to be 100 ms in simulations to minimize the computational cost. The coupler system treatment is an important issue in the assessment of the impact behavior of railway vehicles, since this spring component contacts first in a train impact and it absorbs certain amount of impact energy. Since our main focus is to investigate the worst case to which cars are subjected and cars would be positively affected by the coupler system, the coupler systems are not included in the models. Collision analysis of the railroad passenger car consists of two stages. The crashworthiness of the initial concept design is analyzed in the first stage and the initial design was modified and simulated again under the same conditions in the second stage. As a result of the modifications, the passenger car design with better crashworthiness properties was obtained [14,15] (i.e., see Figure 9). Figure 8 shows the energy absorbed by both the modified and original passenger cars. Over the total crash period, the modified passenger car absorbed total energy of 8.35 MJ, which is 13 percent more than that of the original passenger car.

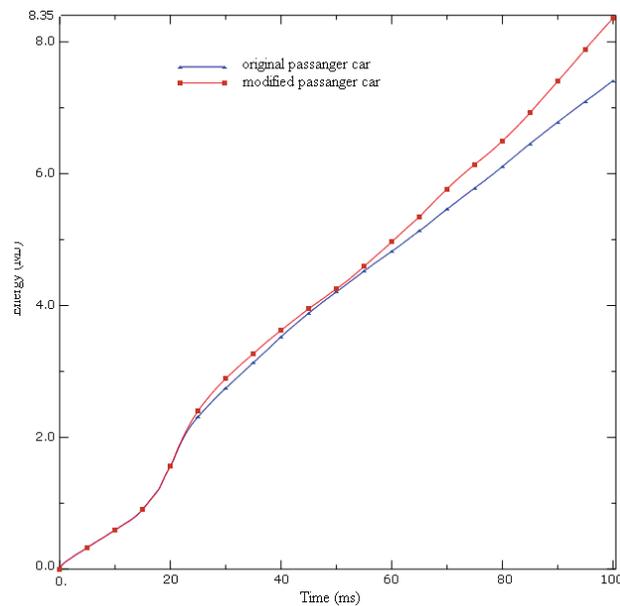


Figure 8 Collision energy absorbed by the modified and original passenger car structure [14].

Figure 9 shows crash response of the original and modified passenger car structures. The end structure of the modified passenger car bodies undergoes progressive deformation damage. Thus, the end structures of the body deforms and collapses like a button box and absorbs crash energy as expected. In addition, it is observed that the cabin was undergone only elastic deformations while the passenger car end area collapsed progressively. Figure 10 shows crash response of the freight cars structure. The end structure of the freight car body also undergoes progressive deformation damage.

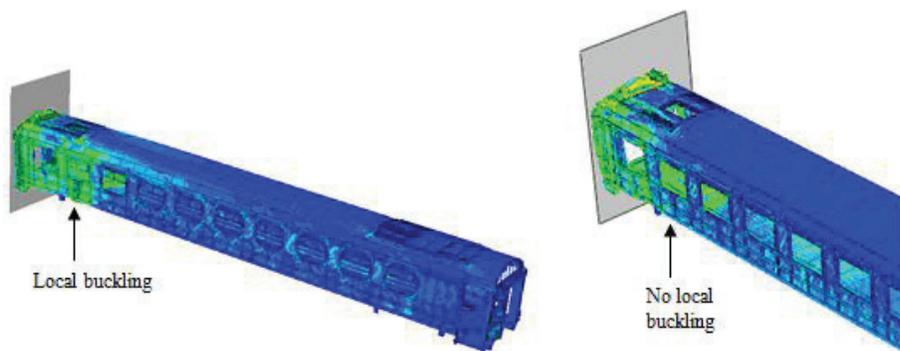


Figure 9 Crash response of the passenger car body; original (left), modified (right) [14,15].

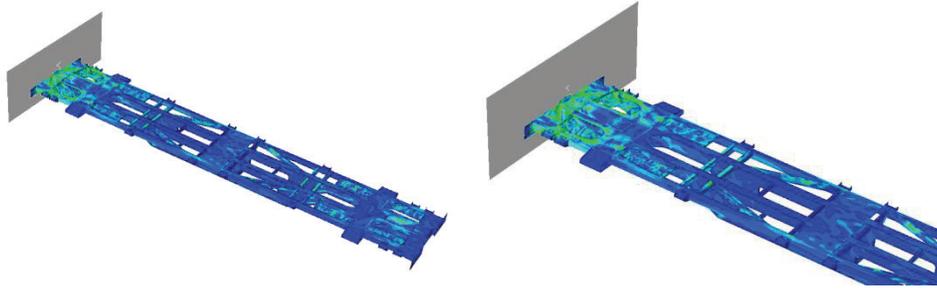


Figure 10 Crash response of the freight car body

3. Conclusion

In this paper, stress, vibration and crash analysis of railway passenger and freight car structures are presented. FE method is used to assess the static and dynamic structural behaviors of railway vehicles and FE models are validated by comparisons with experimental measurements. As a result of relevant simulations, static and dynamic structural characteristics and structural weaknesses of designs are determined. Suggestions for improving dynamic, static and crashworthiness characteristics of rail car structures can be proposed. Working with the FE models saves cost and time during the development processes of railroad vehicles and complex simulations can be performed easily at all stages of design. The simulation procedures used in analyses are the implicit and the explicit methods implemented in Abaqus [25] on a computer having 8 CPUs, 64 GB RAM and 2 TB hard disk capacity.

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