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DEVELOPMENT OF FINITE ELEMENT MODEL OF SHUNTING LOCOMOTIVE APPLICABLE FOR DYNAMIC ANALYSES

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Abstract

The main aim of this study is to develop a finite element model of the hybrid-shunting locomotive. Considered locomotive is based on a popular shunting locomotive in Poland – SM42. All components above the locomotive frame could be modified in comparison to the original object, whereas a chassis was essentially unchanged. Such solution allows the operators freely configure components e.g. diesel engine, generator, cooling module, cab etc., according to their own requirements. Works on the FE model were focused on very accurate reflection of the locomotive frame since the planned dynamic analyses include crash tests. FE model of the frame has a fine mesh and it is considered as a deformable component. Other segments of the vehicle are simplified and treated as rigid bodies mostly. FE model was developed on the basis of the locomotive CAD model. It was decided to transform the CAD model of the frame into the FE one applying the midsurface procedure. Such approach is correct since the locomotive frame is made of a large number of steel elements in the form of sheet metal plates and sections welded together. Altair Hyper Mesh software was used in the FE model developing process. Appropriate connections between respective components of the model e.g. wheelset – bogie, bogie – locomotive frame, were applied. Finally, the locomotive FE model consists of about 116 thousands of finite shell and solid elements and about 125 thousands of nodes. Dynamic analyses of the locomotive FE model will be carried out using LS-DYNA computer code.

Keywords: *finite element method, modelling, dynamic analysis, crash test, railway vehicle, LS-DYNA, Hyper Mesh*

1. Introduction

The PN-EN 15227 standard provides crashworthiness requirements for railway vehicle bodies. It is impractical to evaluate the complete locomotive behaviour by testing therefore the achievement of the objectives can be validated by dynamic numerical simulation [1]. Proposed FE model could not be validate since the real object has not been built yet. Therefore, the authors based on just one criterion related to the total weight of the locomotive during the developing process of its FE model. The designer provided information about the component mass. Moreover, several components of the locomotive were commonly used therefore some technical details were available from the manufacturers or the repair workshops.

There is considered hybrid-shunting locomotive based on a popular diesel-electric locomotive in Poland – SM42. Presented studies are a part of the project focused on modernization of the SM42 locomotive. All components above the locomotive frame e.g. diesel engine, generator could be replaced by the new components – smaller and more eco-friendly diesel engine, higher-class generator and alternative power sources like batteries. Therefore, a classic shunting diesel-electric locomotive became a modernized hybrid one. A chassis of the locomotive was essentially unchanged. Such approach allows the operators to freely configuring components according to their own requirements. Moreover, parameters of the hybrid module could be individually chosen for each locomotive on the basis of the actual power demand resulting from the specifics of the operation work. The SM42 locomotive is depicted in Fig. 1a, whereas the geometrical CAD model of the modernized one – in Fig. 1b. The main differences between these two locomotives – despite

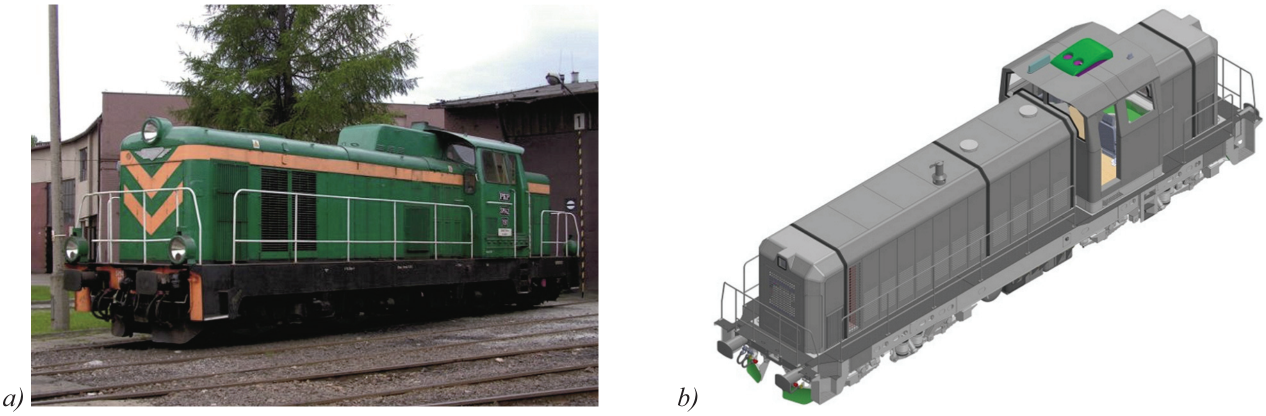


Fig. 1. SM42 diesel-electric shunting locomotive (a) [2] and the CAD model of the modernized hybrid locomotive (b) [3]

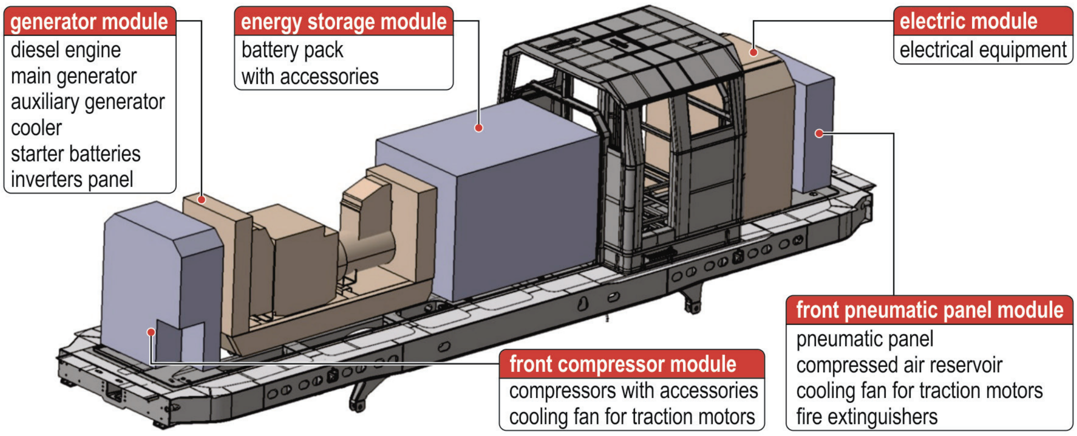


Fig. 2. CAD model of the modernized SM42 hybrid locomotive without bogies, chassis components and skin plate

of the modern bodywork – are a brand new ergonomically designed cab as well as types and location of powertrain modules depicted in detail in Fig. 2.

2. Development of the FE model

Ongoing works on the FE model were focused on very accurate reflection of the locomotive frame. FE model of the frame had a fine mesh and it was considered as a deformable component. Other segments of the vehicle were simplified and treated as rigid bodies mostly. Skin plates were omitted in the FE model. Further studies will include e.g. dynamic analysis such as crash test carried out using LS-DYNA computer code. Buffers absorb a significant amount of the impact energy during the locomotive crash. However, the body frame is also subjected to the impact since the buffers at mounted to the frame.

CAD model of the locomotive was based on solid elements. Since the actual frame is generally made of a large number of steel elements in the form of sheet metal plates and sections welded together it could be modelled using shell finite elements. Transformation from solid objects (CAD model) to the surface model (FEM) required applying of the midsurface procedure in CATIA software. Midsurface is generated between two sidewalls of the solid exactly in the middle distance between them. A fragment of the frame CAD model and schematic description of the midsurface procedure is presented in Fig. 3.

Due to large number of components in the frame and their different thicknesses, it was necessary to diversify frame fragments and collect them with regard to the thickness. Fig. 4 shows the frame surface CAD model. Different colours correspond to different thicknesses of sheet metal in the actual frame.

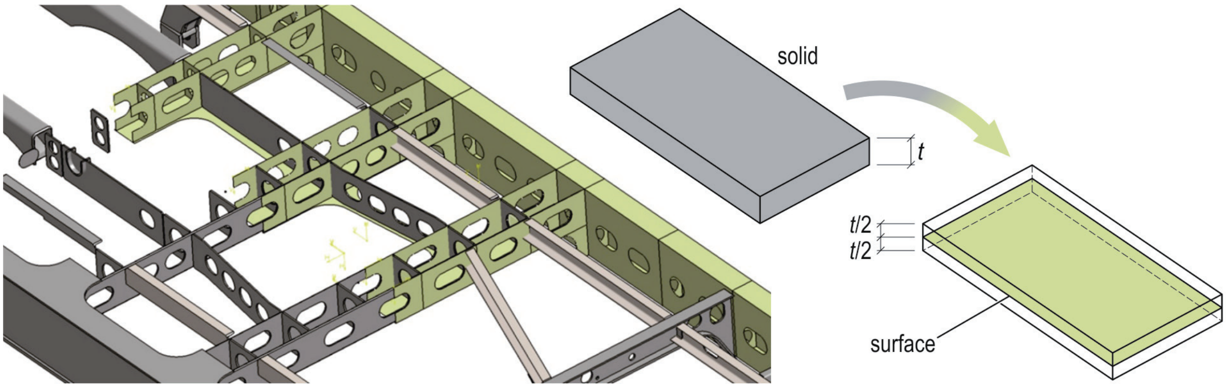


Fig. 3. Frame CAD model with midsurfaces highlighted and description of the midsurface procedure

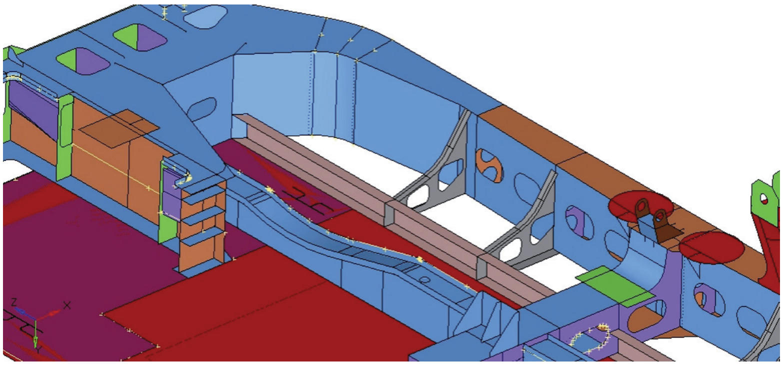


Fig. 4. Frame surface model – colours correspond to different thicknesses of surfaces

Since the shape of the frame is quite complicated (sections, fillets, lots of holes etc.) an automatic meshing could be used only. An average dimension of the finite element is about 30 mm for the frame. The mesh is relatively regular and it includes both triangular and rectangular elements.

FE model of the locomotive frame is depicted in Fig. 5. The frame was considered as a deformable component. *MAT_PLASTIC_KINEMATIC was applied for the whole frame elements. This model is suited to model isotropic and kinematic hardening plasticity [4]. Material properties are provided in Tab. 1. Other components of the locomotive body were treated as rigid bodies except for the extreme modules. All modules depicted in Fig. 2 were simply simulated as blocks and attached to the frame in appropriate mounting points using spot welds.

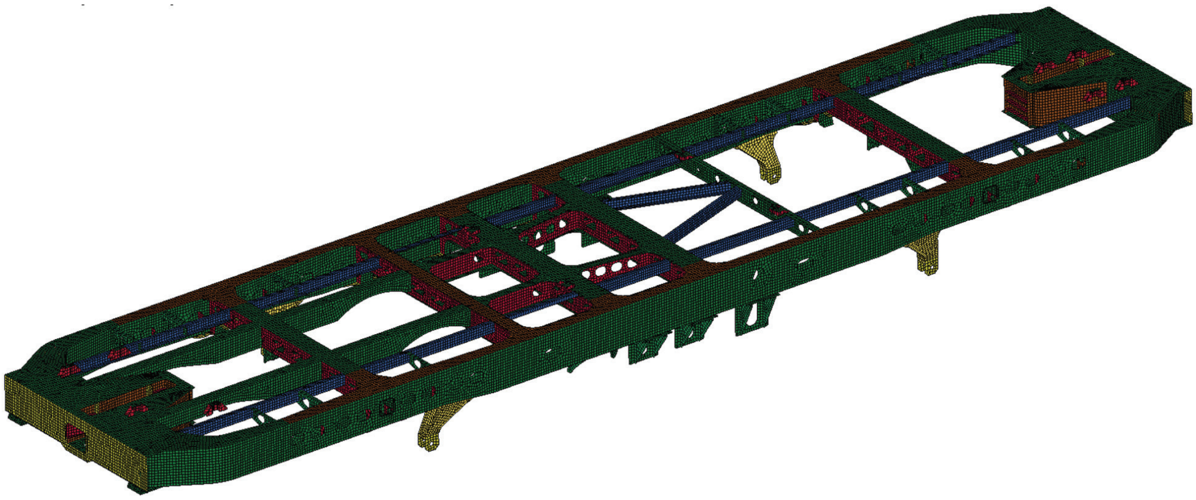


Fig. 5. FE model of the locomotive frame – the floor is not shown to better illustrate the inner parts of frame

Tab. 1. Material properties of steel applied for the frame FE model

Density (kg/mm^3)	Young's modulus (GPa)	Poisson's ratio (-)	Yield stress (GPa)	Tangent modulus (GPa)
7.85×10^{-6}	210	0.3	0.6	1

The modernized hybrid-shunting locomotive is equipped with the classic chassis including two 2-axle bogies. Since the bogie structure was very complicated, some simplification in the FE model had to be assumed (Fig. 6). Springs and dampers were not modelled as 3-D objects. Instead of that 2-node beam elements with the *MAT_LINEAR_ELASTIC_DISCRETE_BEAM material were applied. This material model is defined for simulating the effects of a linear elastic beam by using six springs, each acting about one of the six local degree-of-freedoms [4]. Locomotive has generally vertical springs and dampers therefore the translational stiffness and the translational viscous damper about the *r*-axis (along the beam element axis) was defined. Stiffness for two transverse directions *s*- and *t*-axis was significantly overstated to avoid translation in horizontal plane. The locomotive has two suspension systems – primary suspension system between a wheelset and the bogie frame and the secondary suspension system between the bogie frame and the locomotive frame. Primary suspension system includes two sets of coil springs – the inner and the outer one in each set – and leaf spring per axle box. The secondary suspension system consists of two sets of coil springs – the inner and the outer one in each set – per side of the bogie. Equivalent stiffnesses for each suspension system were determined. Hence, one discrete beam element could be applied instead of set of two springs. Tab. 2 provides equivalent parameters of the primary and the secondary suspension system.

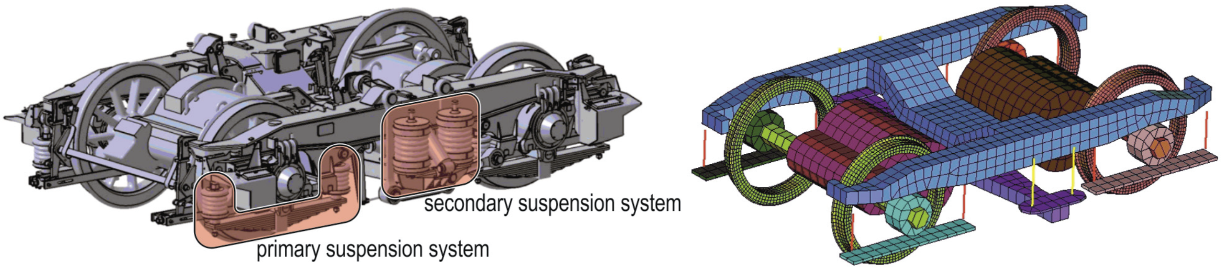


Fig. 6. CAD model of the bogie and its simplified FE model

Tab. 2. Parameters of the locomotive suspension systems

Primary suspension system		Secondary suspension system	
spring stiffness (kN·mm^{-1})	damping coefficient (kN·ms·mm^{-1})	spring stiffness (kN·mm^{-1})	damping coefficient (kN·ms·mm^{-1})
0.614	8	0.675	8

*CONSTRAINED_JOINT_REVOLUTE option was applied to ensure rotation of the wheelsets in the axle box. The same function was assumed for the connection between bogie and the locomotive frame via a pivot. Moreover, the revolute joints were used to suspend the electric motor to the bogie frame (Fig. 7). In some cases, additional extra nodes were generated in order to reduce the complexity of the FE model. Extra nodes – for the rigid bodies only – may be located anywhere even outside the body/component. These nodes are assumed to be a part of respective rigid body. Therefore, there is no apparent connection between some components of the FE model. The buffers are another important element of the FE model because of the impact/crash analysis. Buffers are intended to mitigate the pressure forces and impacts between attached vehicles and to ensure a proper distance between them. In the crash analysis, the buffers absorb a part of the impact energy therefore; they were simulated as deformable bodies. Shell elements were used for the body moreover, the shield of the buffer whereas the 2-node beam element with

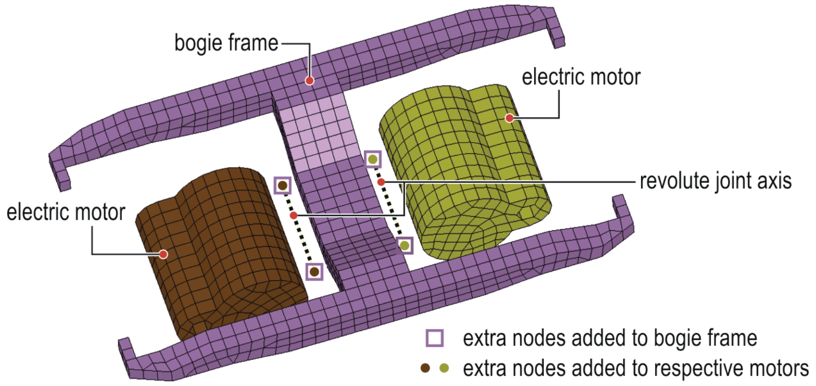
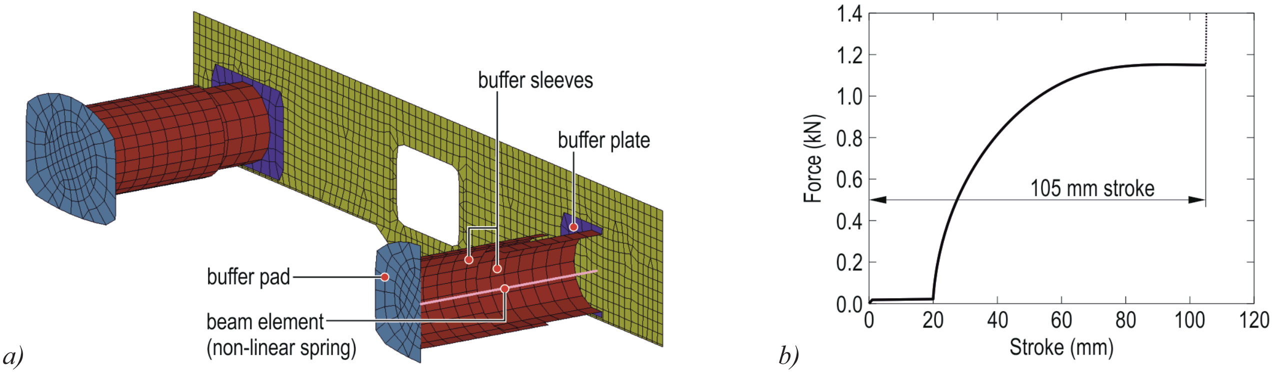


Fig. 7. FE model of the bogie frame and electric motors – explanation of the extra nodes using

the *MAT_NONLINEAR_ ELASTIC_DISCRETE_BEAM material was applied for the energy absorbing element. Locomotive under consideration was equipped with set of two buffers placed on the frontal beams of the frame. Typical buffers with a stroke of 105 mm for locomotives were used. FE model of the buffers is presented in Fig. 8a. Force vs. stroke curve received from the locomotive designer is depicted in Fig. 8b.



a)

b)

Fig. 8. FE model of the buffer (a) and its force vs. stroke curve (b)

Complete FE model of the locomotive under consideration is depicted in Fig. 9. It consists of 115 677 finite elements and 126 391 nodes. 96 550 deformable shell elements was used to simulate the frame and buffers whereas 19 099 solid elements – to simulate other components considered as rigid bodies mostly. 28 beam elements were used to reflect springs and dampers. In addition, about 40-lumped mass were attached to the model to ensure its correct mass. Detailed summary of the FE model is provided in Tab. 3. It can be seen that the locomotive frame includes over 94 thousands of elements grouped in nine parts. Each part is described by different thickness of the shell element.

3. Additional parameters of the FE model

Since the model was planned to use in dynamic analysis including moving of the locomotive it was necessary to declare its velocity. Appropriate card in the LS-DYNA [5] code was applied. Translational velocity of the FE model in global longitudinal direction was defined by the *INITIAL_ VELOCITY option in two steps. Velocity was applied immediately and after dynamic relaxation to all nodes of the locomotive FE model.

*LOAD_BODY option was used to impose gravitational loads on a structure. Vertical direction was specified for the acceleration of 9.81 m/s^2. The load curve was declared with a slow ramp up to avoid the excitation of a high frequency response. Dynamic relaxation was applied to initialize stresses and deformation in the FE model to simulate preload caused by the gravity load.

Tab. 3. Summary of the full locomotive FE model (track FE model not included)

Part ID	Part Name	Element type	Number of elements	Material type	Thickness (shell only)
1	buffers	Shell	1928	plastic kinematic	20.0 mm
2	frame_floor	Shell	1182	plastic kinematic	4.0 mm
3	frame_10	Shell	49 876	plastic kinematic	10.0 mm
4	frame_20	Shell	4942	plastic kinematic	20.0 mm
5	frame_12	Shell	12 964	plastic kinematic	12.0 mm
6	frame_08	Shell	13 478	plastic kinematic	8.0 mm
7	frame_06	Shell	6400	plastic kinematic	6.3 mm
8	frame_05	Shell	2806	plastic kinematic	5.0 mm
9	frame_15	Shell	2414	plastic kinematic	15.0 mm
10	frame_16	Shell	152	plastic kinematic	16.0 mm
11	connectors	Shell	408	plastic kinematic	6.0 mm
12	buffers_spring	Beam	4	nonlinear elastic discrete beam	
13	reservoir_1	Solid	108	rigid	
14	reservoir_2	Solid	288	rigid	
15	reservoir_3	Solid	192	rigid	
16	generator_module	Solid	64	rigid	
17	compressor_module	Solid	180	elastic	
18	storage_module	Solid	75	rigid	
19	cab	Solid	152	rigid	
20	pneumatic_module	Solid	40	elastic	
21	electric_module	Solid	60	rigid	
22	bogie1_frame	Solid	684	rigid	
23	bogie1_wheelset2	Solid	3448	rigid	
24	bogie1_wheelset1	Solid	3448	rigid	
25	bogie1_bolster	Solid	130	rigid	
26	bogie1_wheelset2_axlebox_right	Solid	50	rigid	
27	bogie1_wheelset2_axlebox_left	Solid	50	rigid	
28	bogie1_wheelset1_axlebox_right	Solid	50	rigid	
29	bogie1_wheelset1_xlebox_left	Solid	50	rigid	
30	bogie1_suspension_1st	Beam	8	linear elastic discrete beam	
31	bogie1_motor2	Solid	530	rigid	
32	bogie1_motor1	Solid	530	rigid	
33	bogie1_suspension_2nd	Beam	4	linear elastic discrete beam	
34	bogie2_frame	Solid	684	rigid	
35	bogie2_wheelset2	Solid	3448	rigid	
36	bogie2_wheelset1	Solid	3448	rigid	
37	bogie2_bolster	Solid	130	rigid	
38	bogie2_wheelset2_axlebox_right	Solid	50	rigid	
39	bogie2_wheelset2_axlebox_left	Solid	50	rigid	
40	bogie2_wheelset1_axlebox_right	Solid	50	rigid	
41	bogie2_wheelset1_axlebox_left	Solid	50	rigid	
42	bogie2_suspension_1st	Beam	8	linear elastic discrete beam	
43	bogie2_motor2	Solid	530	rigid	
44	bogie2_motor1	Solid	530	rigid	
45	bogie2_suspension_2nd	Beam	4	linear elastic discrete beam	
		TOTAL	115 677		

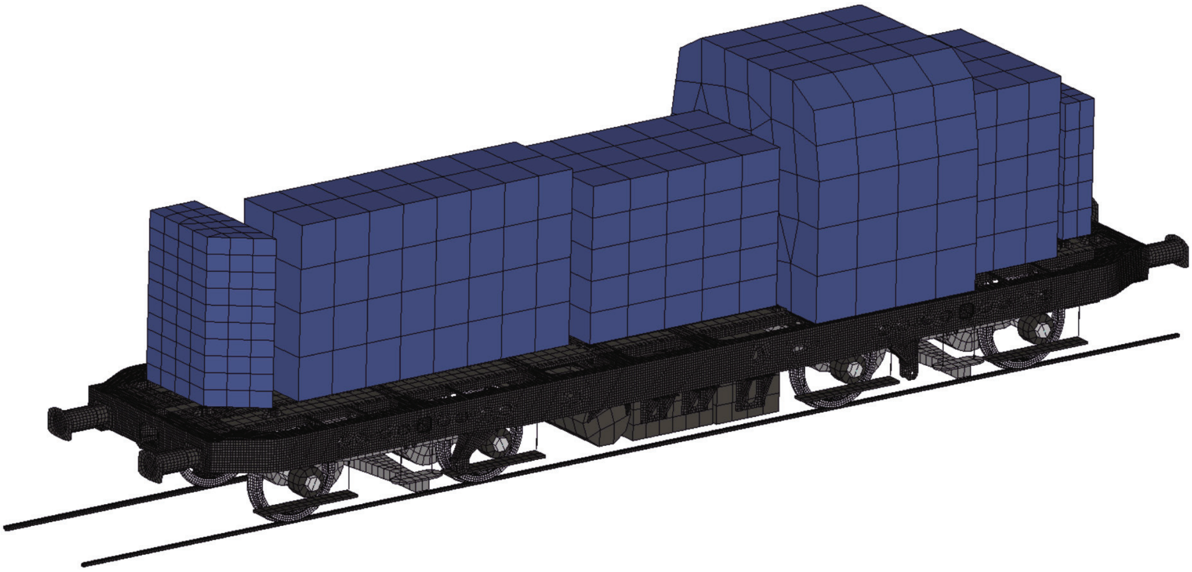


Fig. 9. Complete FE model of the considered locomotive

*AUTOMATIC_SURFACE_TO_SURFACE contact option was used to take the wheel – track interaction into account. Set part of four wheelsets was considered as a slave segment, whereas the track part – as a master one. Scale factors on the master and slave penalty stiffness were both set to 0.5. Friction coefficient of 0.4 was declared in the contact option. Moreover, the contact option was used for the deformable components of the FE model to avoid penetration caused by deformation resulting from the crash test.

Above-mentioned parameters of the FE model are particularly important. Therefore, they are presented in current paper. Other necessary options are typical for such type of analysis. Values of parameters declared in appropriate cards were taken from the LS-DYNA Keyword User's Manual or were based on the authors' experience from previous studies.

4. Summary and conclusion

The paper presents a process of developing of a finite element model of the hybrid-shunting locomotive. Works on the FE model were focused on very accurate reflection of the frame since the planned dynamic analyses include crash tests of the locomotive. Authors decided to simulate the frame using shell elements with different thickness declared since the locomotive frame was made of a large number of steel elements in the form of sheet metal plates and sections welded together. Appropriate connections between respective components of the model e.g. wheelset – bogie, bogie – locomotive frame, were applied using *CONSTRAINED options in the LS-DYNA code. FE model of the locomotive include some simplification caused by the high complexity of the actual object and the CAD model consequently. In some cases, there is no apparent connection between the FE model components or the shape of component does not fully reflect the real object.

The proposed FE model will be used in the dynamic analyses focused on the crash test between a locomotive and road vehicles and between a locomotive and other railway vehicles. These requirements were specified in the European standard [1]. Results of these analyses will be presented in further papers.

In addition, the authors want to carry out quasi-static analysis of the locomotive model to check structural requirements of its body frame [6]. Longitudinal static loads for the considered locomotive are as follows: a compressive force of 2000 kN applied at buffers, a compressive force of 500 kN applied diagonally at buffer attachment, and a tensile force of 1000 kN applied at coupler attachment. All mentioned loads would be considered in combination with the load due to 1 g vertical acceleration of the design mass of the vehicle body in working order.

Acknowledgements

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