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DESIGN OF A METRO DOOR SYSTEM AND DETERMINATION OF MAIN LOADS

Summary. This article discussed the determination of a metro vehicle's door forces acting on its coarse structure. With previous articles addressing this issue, a definition of a specific reference vehicle was provided together with the collection of the normative requirements for metro vehicles. These form a basis for addressing the issue. The main objective hereof was to design a technical solution of a door system for the reference vehicle and create a parametric model of the door's forces acting on the vehicle's rough structure. This model would serve to approximate and operatively quantify these force effects of the door to the vehicle's structure by modifying the various input parameters. Therefore, it was necessary to create a mathematical model of the equilibrium conditions of the proposed door system and to quantify them using a developed software. Subsequently, these results served as inputs for the FEM analysis of the load-bearing components between the door and the vehicle's structure.

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1. INTRODUCTION TO THE METRO VEHICLE DOOR DESIGN

Metro, or underground railway, is one possible solution to the transportation problem faced by large numbers of people in big cities [11,25]. Metro is usually placed in tunnels, therefore, the operational requirements are different from railway vehicles and trams operated on the ground [2,10,14,22,30,32,35]. Vehicles used for metro train-sets have to meet relatively strict criteria as related to the passengers' comfort [8,16,18] and environment [17,19,21]. Furthermore, the metro doors open and close very often and both the door and the door mechanisms are heavily loaded. Thus, the reliability of both elements is of extremely high importance [1,4,9].

The cabin of each wagon is made of large welded extruded aluminium profiles. There are four sliding doors with a width of 1300 mm on both sides of the wagon. The minimum doorway width to allow comfortable entry and exit of the passengers is 800 mm. The door has to have a minimum ground clearance of more than 1900 mm. Furthermore, it must be equipped with a transparent window so that the passengers are able to check the presence of the platform. Safety glass must be used to this end. In addition, a water drain needs to be taken care of. The door system must include a means of diverting water from the vehicle roof, away from the doorway. The door must withstand the force that is generated when a passenger leans or falls against it.

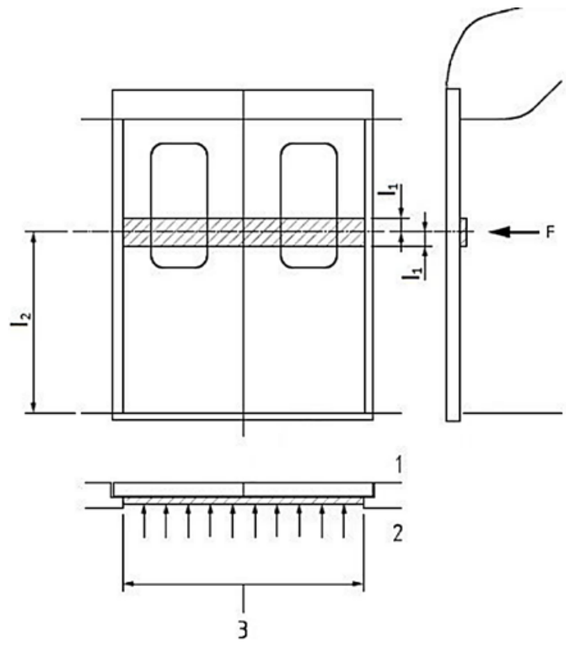

Fig. 1. Point of application of the load generated by the passengers

The force must not cause a non-elastic deformation or the door, which would make it uncontrollable. To this end, a closed and locked door, together with the glass, must withstand the force applied from the interior of the vehicle to the door leaf. This load will be represented by the application of a load on a strip of 200 mm height, located l_2 = 1300 mm above the threshold. The value of this load is 1000 N per each meter of the load mentioned above

(Figure 1: 1 - outer side of the door, 2 - inner side of the door, 3 - uncovered inner area, l_1 = 100 mm, l_2 = 1300 mm, F = 1000 Nm^{-1}). The locking system on the sliding door must withstand a force of 1200 N in the opening direction of opening. Forces in the vehicle equipment handles can be calculated when the mass of the equipment is multiplied by the accelerations occurring in practice, listed in Table 1.

Tab. 1

Considered accelerations

Acceleration in axis.	Accelerati on	Acceleration multiple
x	g	±3
y	g	±1
z	g	1±c

In Table 1, c = 2 g at the end of the vehicle and it decreases linearly up to 0.5 g in the centre of the vehicle, g = 9.81 $m.s^{-2}$.

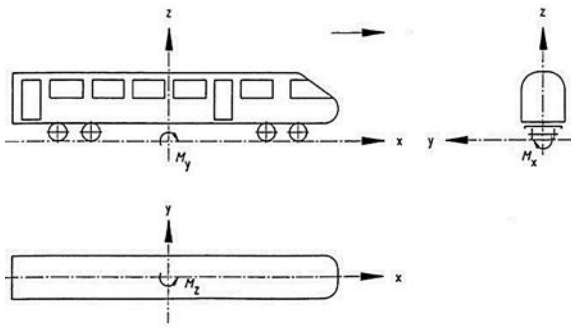

Fig. 2. Vehicle coordinate system

The coordinate system used for calculation is defined in Fig. 2. The positive direction of the x-axis is parallel to the longitudinal axis of the vehicle and is in the travel direction. The y-axis corresponds to the transverse axis of the vehicle and is in the horizontal plane. The positive direction of the z-axis goes upward.

Consequently, numerous requirements must be met, namely those related to fire protection, acoustic and thermal insulation [3,5], electronic devices, reliability, availability, maintainability, safety, protection against current and various environmental conditions and loads caused by vibrations, which rise when riding on a track at various speeds [12,33]. Great emphasis is put on noise protection, as this well-known negative phenomenon is a consequence of every braking process [6,7,24,28].

2. DESIGN OF TECHNICAL SOLUTION FOR THE METRO DOOR

In this section, the technical solution of the metro door system is presented. Its virtual models were made in the CAD software, which is used in the process of the rail vehicles design [26,27].

The designed door system is of a sliding plug door type (Fig. 3). The sliding plug doors work by combining two movements. The first movement pushes the door from the sidewall.

The second movement moves the door alongside the sidewall. The door is ejected in the range from 58 to 65 mm, measured from the sidewall.

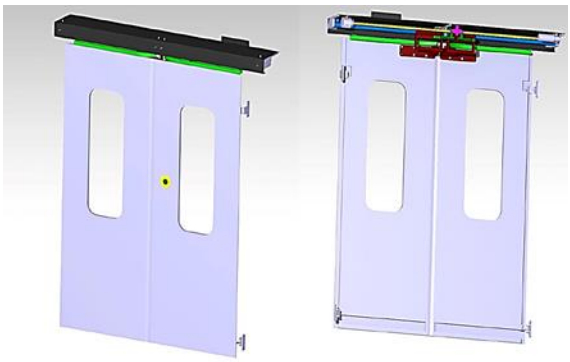

Fig. 3. Designed door system

The main advantage of these doors is that in the closed position, they are located in the plane of the sidewall, therefore, they are suitable for mechanical washing, are more aesthetic and have proper tightness. The disadvantage, in turn, is that the duct or a drive is more complicated than in case of the sliding exterior and pocket doors. The maximum dimensions of the system are the following: width 1856 mm and height 2190 mm. The height of the door leaf is 2077 mm and the width is 781 mm. The weight of the door leaf is 50 kg and of the top of the mechanism is 80 kg. The total weight of the entire system is 180 kg. The system is driven by an electric motor. The power needed to open/close the door is transmitted by means of a screw and guide nuts. The door system is attached to a coarse structure with sixteen M10 screws. The top mechanism contains eight screws - four of them are horizontally screwed into the C grooves on a coarse construction, whereas the other four – vertically. Fig. 4 shows the position of these screws.

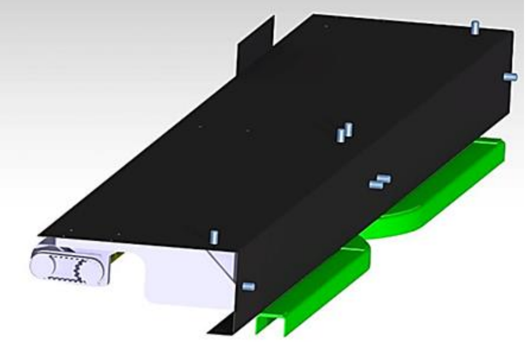

Fig. 4. The position of screws in the door mechanism

The remaining eight screws are located along the sides of the door leaves - four to the right and four to the left. Two of them are used to attach the holding arm, and the remaining two screws are used to attach the arm of the door conduct.

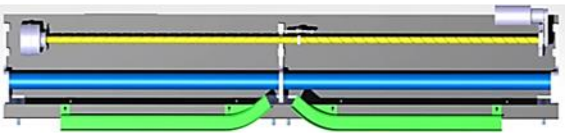

Fig. 5. View of the mechanism from the bottom (without a set of arms)

In the sliding plug door type system, the ejecting movement from the sidewall must be secured. The motion is forced by the shape of guide rails mounted in the top mechanism (Fig. 5).

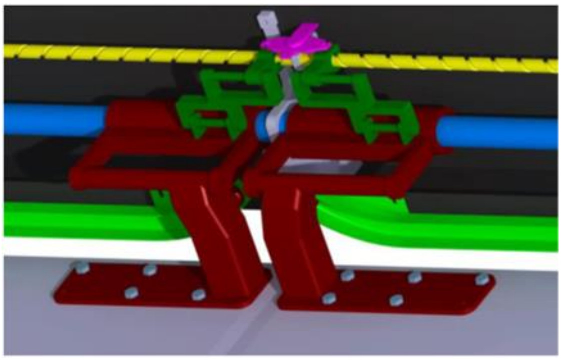

Fig. 6. View of the system of arms

A wheel is mounted on the arm that is screwed to the door leaf in each rail. When moving the guide nut through the bolt when the door is opening, the wheel in the guide rail is forced to extend the door leaf from the plane of the sidewall by curving the guide rail. The force from the guide nut to the door leaf is transmitted by means of a system of arms (Fig. 6). The door leaves are carried by the supporting rod. The door wings are supported by a supporting rod and are slidably and rotatably engaged.

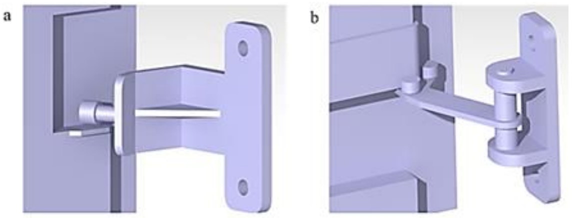

Fig. 7. The holding arm (a), the bottom duct (b)

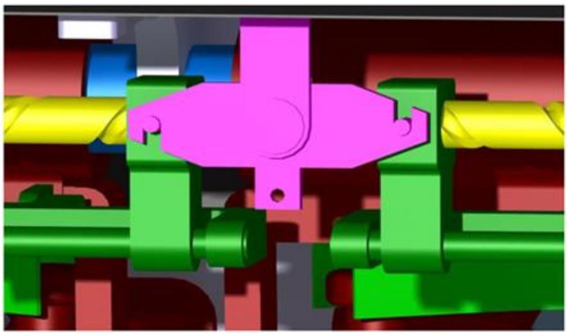

Fig. 8. The lock

The holding arm (Fig. 7a) is not firmly attached to the door; it is attached to the coarse structure and serves to prevent the vertical movement of the door in the direction of the positive axis z. The holding arms are located on the side of both side wings. The bottom duct with a specific rollers layout serves to conduct and support the door when it is being opened or closed.

The bottom duct (Fig. 7b) with a specific rollers layout serves to conduct and support the door when it is being opened or closed and prevents it from moving in the direction of the x and y.

In order to prevent the door from opening automatically, the mechanism is provided with a lock that secures the system in the area of the guide nuts (Fig. 8). The lock is unlocked by applying force to its lower part, for example, using a bowden cable that causes clockwise rotation.

3. PARAMETRIC MODEL

It is assumed that the vehicle is not moving and the doors are closed and locked. We will define the external forces that will be taken into consideration, as well as the reaction forces that represent the action of the door system on the coarse construction. The external forces can act in different combinations. These combinations will be defined in cases of load. The calculation itself, made in Microsoft Excel, will be implemented in the parametric model. This model can be used for a quick calculation of the forces acting on the coarse construction for various load cases, with the possibility of entering the input parameters as required. Fig. 9 presents a simplified calculation model. The positions 1-7, as well as points A, B, C, D, E, F, T1, T2, and T3 (Table 2), are visible.

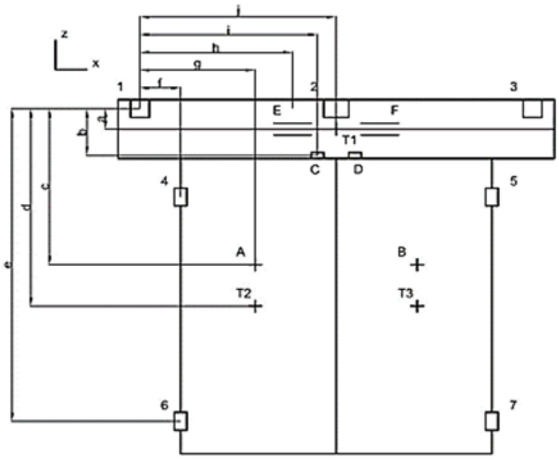

Fig. 9. Model for calculation

Numbers 1-7 represent the areas where the door system is attached to a coarse construction. Strength analyses were calculated for each of these positions.

The individual distances were measured in the CATIA model presented herein (Table 3).

Tab. 2

Description of the individual points

A	The effect of force on the door leaf from a passenger
B	The effect of force on the door leaf from a passenger
C	The point of contact of the guide rail with the guide wheel

D	The point of contact of the guide rail with the guide wheel
E	Sleeve on the carrier rod
F	Sleeve on the carrier rod
T1	The centre of gravity of the top mechanism
T2	The centre of gravity of the door leaf
T3	The centre of gravity of the door leaf

Tab. 3

The distances determined in the Catia model

Distance	Value (m)	Distance	Value (m)
a	0.025	h	0.7435
b	0.098	i	0.8226
c	0.861	j	0.878
d	1.127	k	0.1205
e	2.071	l	0.173
f	0.147	m	0.117
g	0.4875	n	0.06

Positions 1 and 3 in Fig. 9 are identical. It is the place of fixing the door system to a rough construction with two screws. One screw is placed vertically, another one horizontally. Position 2 consists of two vertically and two horizontally positioned screws (Figure 10). In the calculation, it was assumed that all the three positions – 1, 2 and 3, take the degrees of freedom in all three axes.

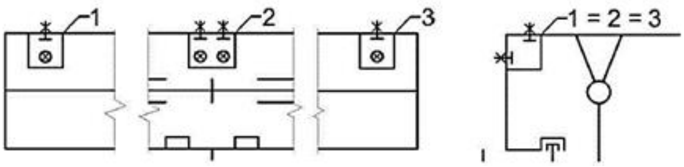

Fig. 10. Details of positions 1, 2 and 3

Positions 4 and 5 (Fig. 9) represent the holding arm. They were not taken into consideration in the equations in every case as they only prevent the door from moving in the positive direction of the z-axis. It is mounted with two screws to the rough construction. Positions 6 and 7 represent the bottom door guides. On the course structure, the force effect is transmitted from the door through the swinging arm. In the closed position of the door, they prevent it from moving in the direction of the x and y axes. It is attached to the course structure with two screws (Figure 11).

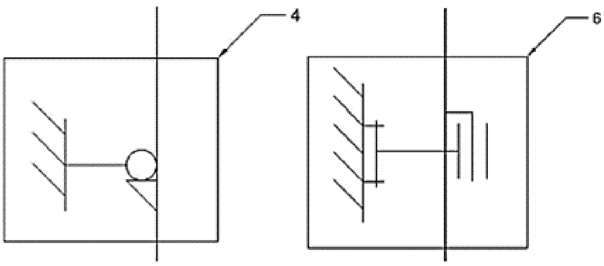

Fig. 11. Details of positions 6 and 7

To obtain a correct and simple solution, it should be determined which load case will be optimal for the overall system. After having analysed the model, it was determined that the optimal load case will be when a course structure will be loaded at all seven points of contact. Therefore, such load variation (the most unfavourable one) has been selected, as shown in Tab. 4.

Tab. 4

Considered accelerations

Acceleration in axis	Acceleration	Acceleration multiple
a_x	g = 9.81 m.s^{-2}	-3
a_y	g = 9.81 m.s^{-2}	-1
a_z	g = 9.81 m.s^{-2}	+3

For an accurate calculation result, it is also necessary to consider the loads from the passengers, namely 1000 N for each meter of the exposed door width in both directions, as well as the force of the door seal, that is, 50 N per each meter of the door leaf seal length and reduced to the centre of the door leaf. Last but not least, it is necessary to consider the forces generated as a result of the difference in the outside pressure relative to the inside of the vehicle, that is, 1900 Pa, and it is needed to apply the effect to the centre of gravity of the door leaves.

The external forces are determined by the standard STN EN 12663 and by some customer requirements. The forces are as follows:

- F_{axi} – forces emerging from acceleration a_x (± 3g) in the x-axis direction acting in the centres of gravity (1):

$$F_{axi} = m_i \cdot a_x \,, \tag{1}$$

where i = 1, that is, top mechanism, 2 – door leaf,

$$F_{ax1} = m_1 \cdot (\pm 3 \cdot g) = 80 \cdot (\pm 3 \cdot 9.81) = \pm 2354 N$$
$$F_{ax2} = m_2 \cdot (\pm 3 \cdot g) = 50 \cdot (\pm 3 \cdot 9.81) = \pm 1472 N \,,$$

- F_{ayi} – forces emerging from acceleration a_y (± 1g) in the y-axis direction acting in the centres of gravity (2):

$$F_{ayi} = m_i \cdot a_y \,, \tag{2}$$

- F_{azi} – forces emerging from acceleration a_z (-1·g a + 3·g) in the z-axis direction acting in the centres of gravity (3):

$$F_{azi} = m_i \cdot a_z \,, \tag{3}$$

- F_{TL} – forces emerging from the pressure differences between the inside and outside of the vehicle p = ±1900 Pa, acting on the door leaves' centres of gravity (4):

$$F_{TL} = p \cdot S \,, \tag{4}$$

where S = 1.622137 m^2 is the inner area of the door,

$$F_{TL} = \pm 1900 \cdot 1.622137 = \pm 3082 N \,,$$

- F_{CES} – forces emerging from passengers ±1000 N per 1 meter of the exposed door width, acting on the points *A* and *B* (Figs. 1 and 9) on the door leaves' centres of gravity (5):

$$F_{CES} = \pm 1000 \cdot l_0 , \tag{5}$$

where l_0 = 0.59 m is exposed door width,

$$F_{CES} = \pm 1000 \cdot 0.59 = \pm 590 N ,$$

- F_{TES} – gasket forces of 50 N per every meter of door leaf seal length acting on the door leaves' centres of gravity (6):

$$F_{TES} = -50 \cdot o_d , \tag{6}$$

where o_d = 3.639 m is the door leaf seal length.

$$F_{CES} = -50 \cdot 3.639 = -182 N .$$

The principle of superposition was used to compile the equations of forces acting on the vehicle's structure. Firstly, the reactions from each external force are determined separately. These are then summarised, according to the general rules. Determination of the reaction effects due to the acceleration a_x = -3·g can be seen below (Fig. 12).

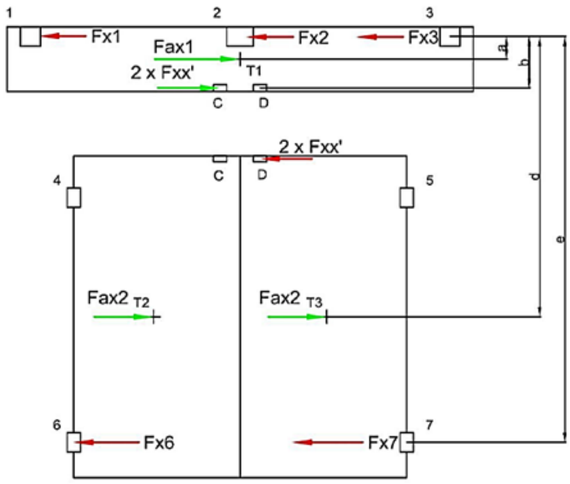

Fig. 12. A free-body diagram of the door when a_x = -3 g

Due to a large number of the reaction effects, the calculation seems to be complicated. However, by introducing certain simplifications and using this symmetry, this can be avoided with a little impact on the calculation accuracy. It can be assumed that (7):

$$F_{x1} = F_{x2} = F_{x3} , \tag{7}$$

and (8):

$$F_{x6} = F_{x7} . \tag{8}$$

For the upper part of the doors, it is as follows (9):

$$\sum_i F_{ix} = 0 \Rightarrow F_{ax1} + 2 \cdot F_{xx}^{'} - 3 \cdot F_{x1} . \tag{9}$$

And for the lower part (10) (11):

$$\sum_i F_{ix} = 0 \Rightarrow F_{ax2} + F'_{xx} - F_{x6} = 0\,. \tag{10}$$

$$\sum_i M_{i6} = 0 \Rightarrow F_{ax2} \cdot (e-d) - F'_{xx} \cdot (e-b) = 0 \tag{11}$$

The forces transferred to the y-direction through the inclined plane on the guide rail (Fig. 13) should also be calculated.

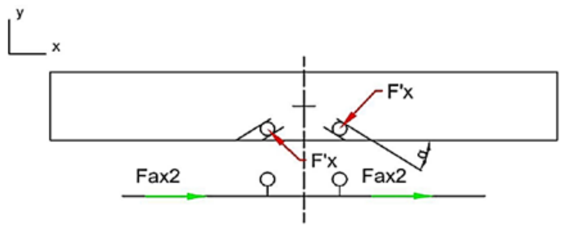

Fig. 13. Reaction forces on the inclined plane of the guide rails when a_x = -3 g

Since the y-components of F'_x (F'_{xy}) reactions are oriented opposite to each other, it can be concluded that reactions on one side of the system will have exactly the opposite direction as the reactions on the other side ($F_{y3} = -F_{y1}$, $F_{y7} = -F_{y6}$).

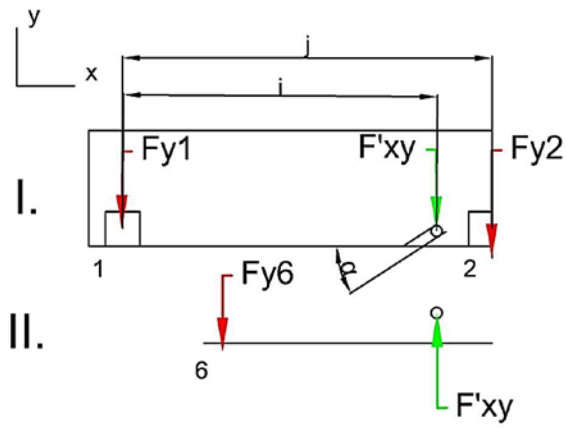

Fig. 14. Force reactions transferred to the y-direction emerging from ax = -3 g

In this case, there is a need to calculate a half of the model only, as the second half is identical as far as geometry and load are concerned. It can be assumed that (12), (13), (14), (15) and (16):

$$F_{y3} = -F_{y1}\,, \tag{12}$$

$$F_{y7} = -F_{y6}\,, \tag{13}$$

$$F'_{xy} = F'_x \cdot \cos\alpha\,, \tag{14}$$

$$F'_{xx} = F'_x \cdot \sin\alpha\,, \tag{15}$$

$$F'_{xy} = \frac{F'_{xx}}{\tan\alpha}\,. \tag{16}$$

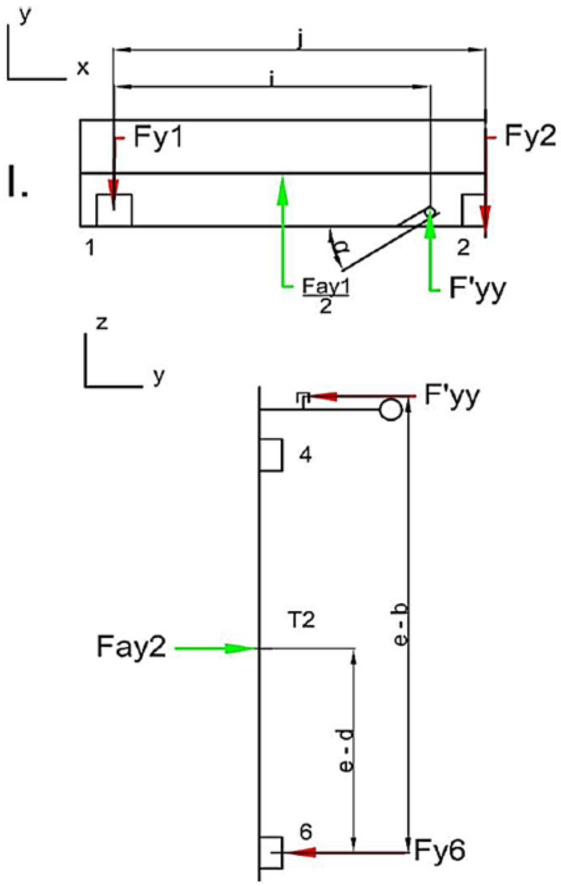

Fig. 15. Free-body diagram for a_y = -1 g

For the first body (Fig. 14 - the upper body) it is as follows in (17) and (18):

$$\sum_i F_{iy} = 0 \Rightarrow -F_{y1} - \frac{F_{y2}}{2} - F_{xy}^{'} = 0\,, \tag{17}$$

$$\sum_i M_{i1} = 0 \Rightarrow F_{xy}^{'} \cdot i - \frac{F_{y2}}{2} \cdot j = 0\,. \tag{18}$$

For the second body (Fig. 14 – the lower body) it is as in (19):

$$\sum_i F_{iy} = 0 \Rightarrow F_{xy}^{'} - F_{y2} = 0\,. \tag{19}$$

Based on Fig. 15, it can be concluded again that only half of the model is necessary for the calculation, due to the symmetry of both parts. Therefore, the next equations apply (20) and (21):

$$F_{y1} = F_{y3}\,, \tag{20}$$

$$F_{y6} = F_{y7}\,. \tag{21}$$

For the upper body from Fig. 15 equations, (22) and (23) apply:

$$\sum_i F_{iy} = 0 \Rightarrow \frac{F_{ay1}}{2} + F_{yy}^{'} - F_{y1} - \frac{-F_{y2}}{2} = 0\,, \tag{22}$$

$$\sum_i M_{i1} = 0 \Rightarrow -\frac{F_{ay1}}{2} \cdot \frac{j}{2} - F_{yy}^{'} \cdot i + \frac{F_{y2}}{2} \cdot j = 0\,. \tag{23}$$

For the lower body from Fig. 15, (24) and (25) can be applied:

$$\sum_i F_{iy} = 0 \Rightarrow F_{ay2} - F'_{yy} - F_{y6} = 0, \tag{24}$$

$$\sum_i M_{i6} = 0 \Rightarrow F_{ay2} \cdot (e-d) - F'_{yy} \cdot (e-b) = 0. \tag{25}$$

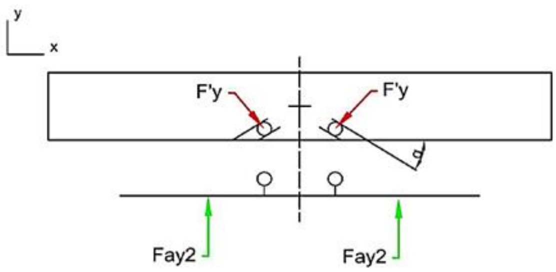

Fig. 16. Reaction forces on the inclined plane of the guide rails when a_y = -1 g

In Fig. 16, it can be seen that the forces transmitted to the x-axis through the inclined plane of the guide rail cancel each other. For the force effects emerging from az = +3 g, according to Fig. 17, (26) and (27) will apply:

$$F_{z1} = F_{z3}, \tag{26}$$

$$F_{z4} = F_{z5}. \tag{27}$$

The equilibrium conditions for the upper body in Fig. 17 are (28) and (29):

$$\sum_i F_{iz} = 0 \Rightarrow F_{z1} - \frac{F_{z2}}{2} + F'_z + \frac{F_{az2}}{2} = 0, \tag{28}$$

$$\sum_i M_{i1} = 0 \Rightarrow F_{z2} \cdot \frac{j}{2} + F'_z \cdot h - \frac{F_{az1}}{2} \cdot \frac{j}{2} = 0. \tag{29}$$

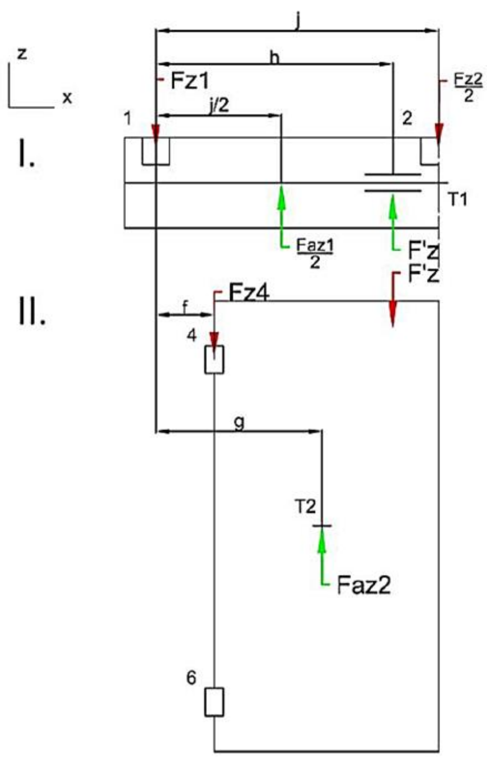

Fig. 17. Reaction forces in the door system when a_z = 3 g

The equilibrium conditions for the lower body in Fig. 17 are (30) and (31):

$$\sum_i F_{iz} = 0 \Rightarrow -F_z^{'} - F_{z4} + F_{az2} = 0\,, \tag{30}$$

$$\sum_i M_{i1} = 0 \Rightarrow -F_{az2} \cdot (g - f) + F_z^{'} \cdot (h - f) = 0\,. \tag{31}$$

Our future activities in this field will include the stress analyses of the designed structure, using the finite element method. Also, since there is a structure [29,31,34] that will be also submitted to the dynamic loads, investigation of the modal properties [13] and creation of a multi-body system for identification of the dynamic properties will be performed [15,20,23].

4. CONCLUSION

This article dealt with the design of a technical solution for the metro vehicle doorway. The designed door was of the forward-sliding type. The advantages of this type of door include aesthetics, tightness, sound and thermal insulation, maintenance costs and small installation space. Also discussed was the creation of a parametric model for calculating the external and reaction forces representing the action of a door system on a vehicle's structure. Presented therein was the creation of the first three loading force effects, namely, the inertial effects of the door's own mass in all three directions (x, y, z). The individual door system dimensions were defined and identified using the Catia model. The prepared part of the parametric model was used in conjunction with other force effects from passengers, gaskets and overpressure to calculate the individual effects on the door system suspension.

A parametric model was created in Microsoft Excel and all the equations (1-31) that were compiled will be converted into a matrix form. The software will calculate the unknown variables by searching for the inverse matrix of inputs. This model should be used to approximate and quickly quantify the force effects of the door on the vehicle's structure when changing different parameters. After obtaining all the necessary equations, these will be organised and arranged as clearly as possible for future use. Finally, the compiled model of the equation enumerates and suggests the components that enable the safe use of the door system in operation. This will be verified for strength analysis by the FEM software.

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