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FEM used for Strength-Related Calculations of Adhesive Joints in the Making of Rail Vehicles

Abstract: The article presents a thick-layer flexible bonding used in railway engineering when making rail vehicles and indicates strength-related requirements for adhesive joints. The FEM was used for testing an adhesive joint between a windowpane and display-mounting brackets. Research-related tests revealed the lack of exceedings as regards acceptable stresses and strains in a tested adhesive joint.

Keywords: FEM, Finite Element Method, adhesive joints, rail vehicles production

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Introduction

Presently, all areas of the Polish railway sector are undergoing vast modernisation, enabling further development by train manufacturers and suppliers of related equipment. In the space, aviation, automotive and railway industries, the reduction of weight without compromising mechanical properties is of great importance. This entails the use of new materials and the replacement of previously used joining techniques (fusion welding, pressure welding, soldering and brazing) with adhesive bonding. One of the most important advantages of adhesive bonding is the possibility of joining materials characterised by various physicochemical properties [2]. Manufactures of elements utilising adhesive joints are required to demonstrate the stability of adhesive joints by conducting computational strength-related analyses or performing experimental tests on actual objects. In railway engineering such requirements are primarily concerned with class A1 and A2 adhesive joints (Table 4) [5], e.g. joints connecting a display to a windowpane inside a car (class A2) (Table 5) [5].

Flexible Thick-Layer Adhesive Bonding in Railway Engineering

Flexible thick-layer adhesive joints have a thickness exceeding 1.5 mm and are made using an adhesive. These joints, once hardened, are characterised by flexible properties and resistance to variable sliding strains above 15% of the joint thickness, on a permanent and failure-free basis.

Applications of flexible adhesive bonding are the following:

- adhesive bonding of external sheathing elements of the vehicle supporting structure,
- adhesive bonding of windowpanes into appropriate cut-outs,
- adhesive bonding of complex component modules into the vehicle body,
- adhesive bonding and fixing of internal screens.

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Processes of thick-layer adhesive bonding are usually based on single-component polyurethane adhesives hardening through contact with water vapour present in the surrounding air. Hardening times can be reduced by the application of heat. Thick-layer adhesive bonding also utilises silicon-hydrogen MS polymers, e.g. when fixing various types of metal shapes and strips [1, 2].

Flexible thick-layer adhesive bonding joins various materials such as steel, aluminium alloys or glass-fibre reinforced plastics (GFRP) with a partial or complete varnish coat.

Design of Adhesive Joints

An adhesive joint should be designed in a manner which, on one hand, would permanently transmit forces corresponding to loads and, on the other, would not fail due to relative displacements of joined elements. A very important design parameter of an adhesive joint is to provide a sufficiently large adhesive bonding area ensuring the safe transfer of service loads.

Maximum permissible stresses (along with a safety coefficient) are determined through experimentation when testing specimens similar to actually used elements. An important factor is to adjust mechanical, chemical, time-related and physical conditions to loads corresponding to actual operating conditions. Mechanical conditions include tensile states, multiaxial stress states etc., chemical conditions include the exposure of adhesive joints to environmental factors, physical conditions are concerned with, among other things, temperature and UV radiation, whereas time-related conditions include static, impact and vibratory states. The thickness of an adhesive layer is another very important design parameter of an adhesive joint because of possible relative displacements between adhesive-joined elements. Particularly large displacements accompany the joining of very large surfaces areas of materials having various thermal expansion coefficients, e.g. a sandwich type roof with the steel structure of a car body.

When designing a joint, it is necessary to know the permissible strains of the hardened adhesive. Usually, such data are provided by the adhesive manufacturer, yet if such information is not available, initial calculations should adopt the maximum relative displacement of joined elements by a value of 15% of the adhesive layer thickness in cases of displacement and by 6% in cases of pulling and pressure.

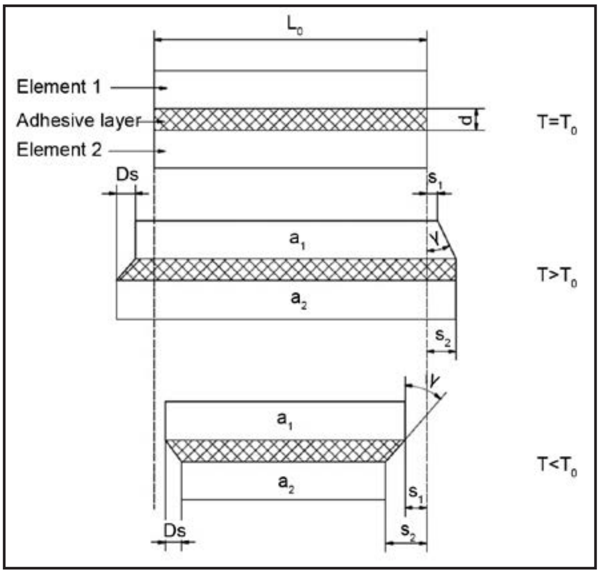


Fig. 1. Temperature-triggered displacement of adhesive bonded elements [7]

The displacement of adhesive bonded elements caused by elongations resulting from the effect of temperature (Fig. 1) is calculated using the following dependence (1):

$$Ds = s_2 - s_1 = \frac{1}{2} L_0 \, (T - T_0)(\alpha_2 - \alpha_1) \qquad (1),$$

where
- L – length of an element at an operating temperature [mm],
- T – operating temperature of both adhesive bonded elements [K],
- L_0 – length of an element at a adhesive bonding temperature [mm],
- T_0 – adhesive bonding temperature [K],
- α – thermal expansion coefficient [$\frac{1}{K}$],
- s – displacement caused by the temperature on the element edge [mm],
- d – adhesive layer thickness [mm],
- Ds – displacement of adhesive bonded elements [mm].

The minimum adhesive layer thickness is calculated using the following dependence (2):

$$d_{\min} = \frac{Ds}{tg\,\gamma} \qquad (2)$$

where γ – angle of a non-dilatational strain.

Process of Thick-Layer Adhesive Bonding

The process of adhesive bonding should involve the use of fixtures meeting the requirements of an adhesive bonding operation and be performed on a station satisfying related conditions of purity, treatment and occupational hygiene. In order to provide stable conditions, adhesive bonding should be performed in special rooms protected from dust as well as rapid temperature and humidity changes. This principle is primarily applied when using 1-component adhesives hardening by absorbing humidity from air. During hardening, an adhesive joint cannot be exposed to any mechanical stresses favouring the generation of disadvantageous states of strains and stresses in adhesive layers.

Adhesive bonding can be performed using wet or dry methods. Wet adhesive bonding consists in applying a bead of adhesive on an appropriate surface followed by the joining of elements. During bonding, it is necessary to force an adhesive and to prevent the displacement of elements being joined. "*The thickness of an adhesive bead should correspond to the average double thickness of the adhesive. However, the greatest adhesive thickness obtained cannot exceed ²/₃ of the beam height as otherwise the adhesive will not be adequately pressed thus insufficiently adhering to the surface of elements being joined*" (DVS 1618, 2002) [7] (Fig. 2).

In dry adhesive bonding, the surfaces of elements to be joined are placed in the final position in relation to each other. An appropriately wide gap is ensured by using appropriate spacers. An adhesive is applied by being injected using special guns. An adhesive is additionally pressed (using a spatula) to properly adhere to the surfaces of elements being joined. This process should not involve the use of any smoothing agents as this could impede adhesion to the sealing material applied in the next process (Fig. 3).

A very important aspect related to adhesive application is the use of spacers, usually having a Shore hardness value similar to that of the hardened adhesive. Spacers, used in order to ensure a constant adhesive gap of a minimum width, should be placed as far outside the adhesive joint as possible.

The use of spacers is accompanied by the use of PUF filling shapes of closed pores applied as limiters to the adhesive during dry adhesive bonding and facilitating pressing the adhesive with a spatula (Fig. 4).

"*Rear filling shapes should not be pushed between an adhesive and a leak stopper as otherwise water entering because of a local defect will be spread*

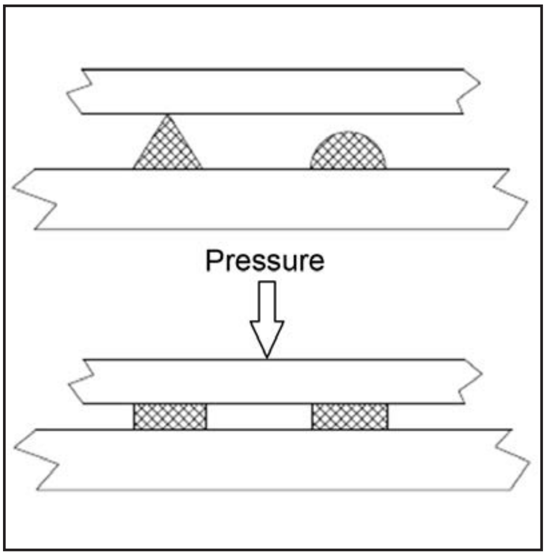


Fig. 2. Wet adhesive bonding [7]

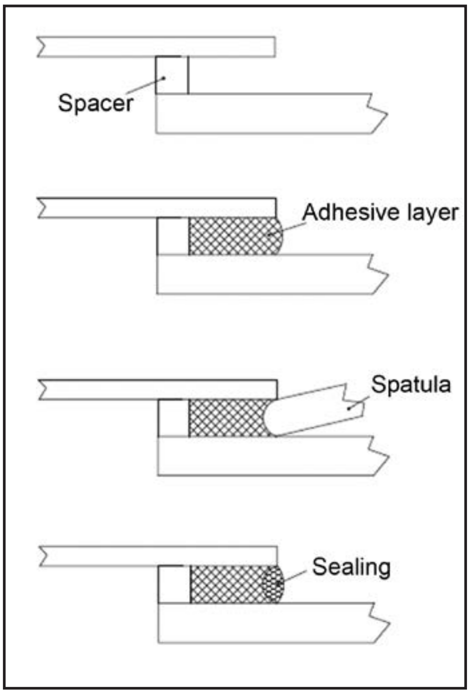


Fig. 3. Dry adhesive bonding [7]

over the entire adhesive joint and will not be able to evaporate" (Dvs 1618, 2002) [7].

Protection of Adhesive Layers against UV Radiation

As applied polyurethane adhesives are usually unstable when exposed to UV for a longer time, when adhesive bonding elements permeable to light (e.g. windowpanes) it is necessary to properly protect an adhesive layer against UV. Such a requirement can be satisfied by using an external coat complying with the dependence of *U*=2x*d*, where *d* is the thickness of a single or double windowpane (Fig. 5). This condition is dictated by the necessity of protecting the adhesive against sun radiation hitting the windowpane obliquely [7].

As regards TSG (toughened safety glass) or LSG (laminated safety glass) windowpanes, i.e. windowpanes made of glass panes joined using a special foil, the layer of adhesive can be protected by ceramic screen printing applied on the external side of a windowpane. Such a solution can be used if appropriate impermeability to light, e.g. transmission below 0.1% over the area can be ensured [7].

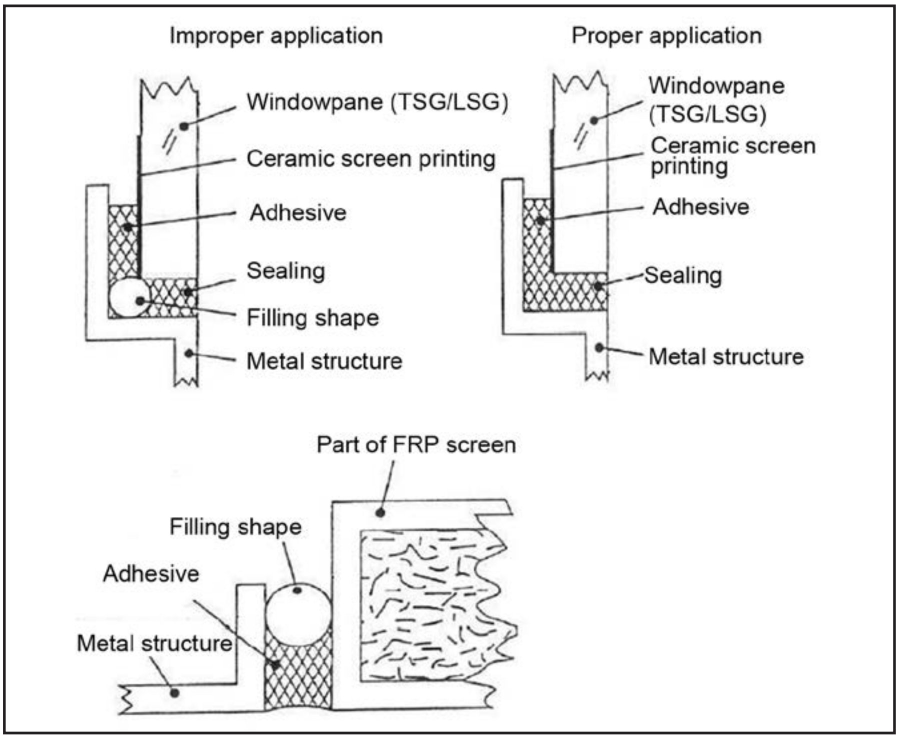


Fig. 4. Manners of applying rear filling shapes: a – improper application; b, c – proper application [7]; (FRP – German Faserverbundwerkstoff (fibre-reinforced plastic) – fibre-reinforced composite material [7])

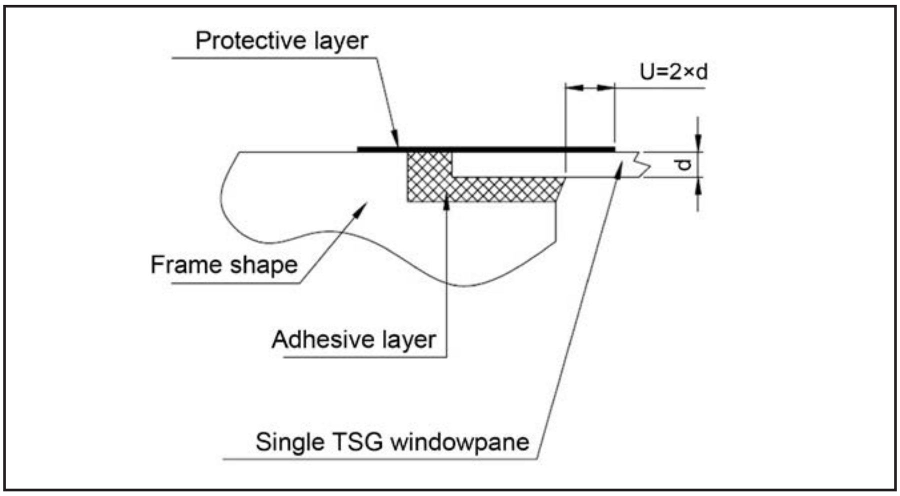


Fig. 5. Protection against UV radiation when a single windowpane is used [7]

Mechanical Properties

Due to the production character of companies, the primary focus of this work is on requirements related to the mechanical properties of additional structural elements such as doors or windows mounted in a car body. Table 1 presents individual stresses for additional elements resulting from the operation of vehicles.

Table 1. Maximum service loads of elements mounted in a car body [6]

Element	Load	Remarks
Entrance and cargo doors	2500 Pa[1] or 1900 Pa[2]	It is necessary to add a concentrated force of 800 N applied in the middle of a door leaf
Windows	2500 Pa[1] or 1900 Pa[2]	

[1] for a speed of v=200 km/h on a slow route inclusive a wind pressure of 700 N/m

[2] for a speed of v=160 km/h on a slow route inclusive a wind pressure of 700 N/m

In addition to the above named stresses in the form of pressure affecting a car body when vehicles pass, strength-related calculations should take into consideration the following gravitational loads:

- in the longitudinal direction:

$$F_x = m_1 \times 5g \text{ [N]} \quad (3)$$

- in the transverse direction:

$$F_y = m_1 \times g \text{ [N]} \quad (4)$$

- in the vertical direction:

$$F_z = m_1 \times c \times g \text{ [N]} \quad (5)$$

where
m_1 – weight of a structural element,
g – gravitational acceleration,
c – coefficient.

Figure 6 presents the coordinate system of a passenger car.

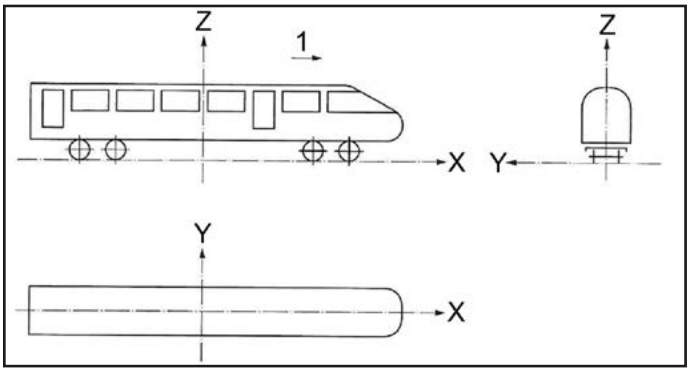


Fig. 6. Coordinate system of a passenger car [8]

Adhesive Joint Control

The control of an adhesive and the assessment of its adhesion to various surfaces are performed in a so-called adhesive strip test (Fig. 7). To this end, it is necessary to use materials, the surfaces of which must be prepared in accordance with joining techniques applied in railway engineering. During a test, a cylindrical-shaped bead of adhesive having a cross-sectional area of 10 mm² and a length of at least 50 mm is applied to the surface of a given material. When applying, the adhesive should properly wet the base. If necessary, an adhesive can be spread by means of a wooden spatula. The adhesive should form a smooth layer having a thickness of approximately 5 mm. The hardening of the adhesive, occurring in the conditions and time specified by the manufacturer, is followed by the assessment of its adhesion. "*The adhesion is verified by cutting through the bead obliquely to the adhesive bonding surface and tearing the adhesive away, using pliers, at an angle of 130° and 160°. In varnished or grounded specimens, cuts should be made on the supporting base. When subjected to pulling off, the bead should be cut between 5 mm and 10 mm in the direction transverse to the base. The making of each cut should be preceded by a pause of 3 seconds, during which the material is subjected to a further load. The length of an adhesive bead put to the test should amount to a minimum of 50 mm*" (DVS 1618, 2002).

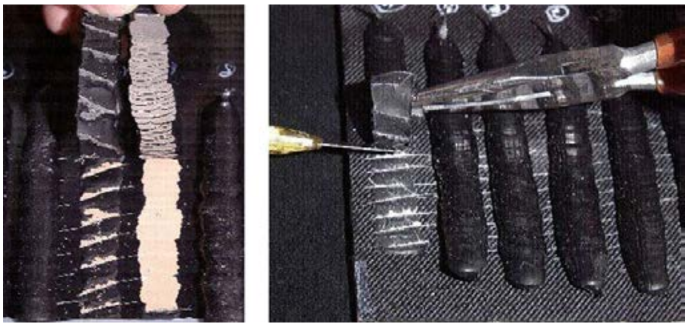


Fig. 7. Adhesive strip test [7]

In addition to being subjected to adhesive strip tests, adhesives are also tested for their long-term service life. Each specimen is subjected to successive ageing cycles (Table 2). Individual stages finish with a visual assessment of a cohesive fracture (see Table 3).

Classification of Adhesive Joints

As regards safety, adhesive joints of railway vehicles and their components are divided into three classes, i.e. A1, A2 and A3 (Table 4). Examples of adhesive joints and related classes are presented in Table 5.

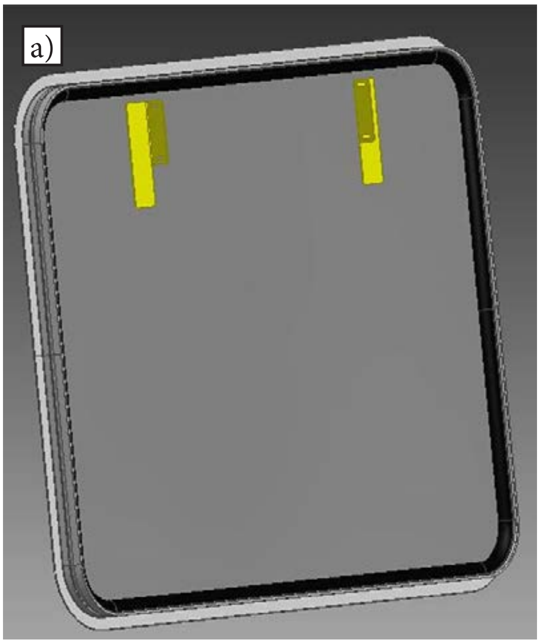
FEM-based Tests of a Selected Adhesive Joint

Finite Element Method-based tests utilising a Siemens NX9.0 software application were

Table 2. Sequence of adhesive ageing tests [7]

Test no.	Type of treatment
1.	7 days at a temperature of 23°C /50 - 2% of relative humidity (according to DIN 50014)
2.	7 days subjected to the effect of distilled water at a temperature of 20°C, additionally 2 hours at 23°C /50 - 2% (according to DIN 50014)
3.	1 day at a temperature of +80°C (immediate check)
4.	2 hours at a temperature of 23°C /50 - 2% (according to DIN 50014)
5.	7 days at a temperature of 70°C in saturated humidity (Cataplasma) + 2 hours at 23/50 - 2% (according to DIN 50014 – process E2), relatively fast cooling to -30°C

performed to examine an adhesive joint between a windowpane and brackets supporting a display having a weight of approximately 7 kg [1]. Figure 8 presents a geometrical model of a display window and an appropriately simplified discrete model with a mesh.



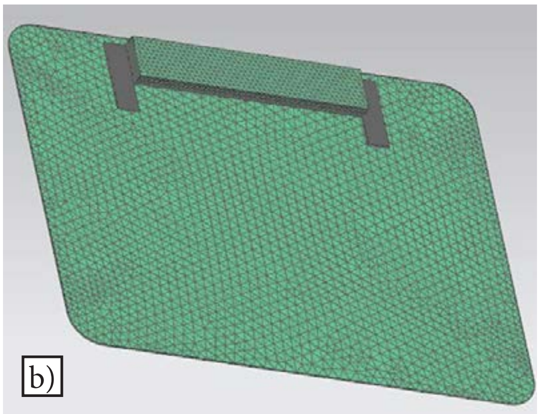


Fig. 8. Models of a window subjected to analysis, view from inside the vehicle: a) geometrical model, b) discrete model

Table 3. Assessment of the cohesive fracture of an adhesive joint [4]

No.	Assessment	Fracture
1.	adhesion: very good	95% – cohesion
2.	adhesion: good	95 > 75% – cohesion
3.	adhesion: poor	75 > 25% – cohesion
4.	adhesion: very poor	< 25% – cohesion

Table 4. Classification of adhesive joints according to DIN 6701-3: 2010 [5]

Class	Description	Safety requirements
A1	adhesive joints of railway vehicles with high safety requirements	**High safety requirements,** the lack of an adhesive joint leads to an immediate health and life hazard or poses a hazard to the safety of a railway company
A2	adhesive joints of railway vehicles with medium safety requirements	**Medium safety requirements,** the lack of adhesive joints may put a railway company at risk related to personnel or result in the loss of the general function of railway vehicles
A3	adhesive joints of railway vehicles with low safety requirements	**Low safety requirements,** the lack of adhesive joints leads to the maximum loss of comfort. Personal losses are highly unlikely

Table 5. Exemplary adhesive joints according to joint safety classes [5]

Joint safety class	Examples
A1	- windscreen in a structural bonnet - side window in a car body - car body structural frame
A2	- internal equipment elements, e.g. hangers, compartment partitions, screens - fastenings connecting seats to the floor
A3	- signboards - mirrors - floor finish

Table 6. Permissible deflection of a windowpane subjected to pressure [6]

Deflection in the centre [mm]	**Smallest dimension for a width or height [mm]**
5	up to 350
7	350-600
10	600-1000

Table 7. Cases of windows loaded with gravitational forces

Case no.	**Load in direction *X*, a_x [m/s²]**	**Load in direction *Y*, a_y [m/s²]**	**Load in direction *Z*, a_z [m/s²]**
1			+1g
2			-3g
3		+1g	-1g
4		-1g	-1g
5	+5g		-1g
6	-5g		-1g

Table 8. Cases of exposure to pressure

Case no.	**Pressure load [Pa]**
7	+1900
8	-1900

Table 9. Maximum stresses and strains of a windowpane

Case no.		Reduced von Misses stresses [MPa]	Principal stresses [MPa]	Displacements [mm]
1	$a_x = 0$ $a_y = 0$ $a_z = 1\times g$	5.8	0.3	$U_x = -0.003 \div 0.003$ $U_y = -0.018 \div 0.008$ $U_z = 0 \div 0.016$
2	$a_x = 0$ $a_y = 0$ $a_z = -3\times g$	17.37	1.27	$U_x = -0.008 \div 0.008$ $U_y = -0.023 \div 0.053$ $U_z = -0.048 \div 0$
3	$a_x = 0$ $a_y = 1\times g$ $a_z = -1\times g$	10.15	3.66	$U_x = -0.003 \div 0.004$ $U_y = 0 \div 0.315$ $U_z = -0.044 \div 0.003$
4	$a_x = 0$ $a_y = -1\times g$ $a_z = -1\times g$	4.86	3.23	$U_x = -0.005 \div 0.006$ $U_y = -0.29 \div 0$ $U_z = -0.007 \div 0.013$
5	$a_x = 5\times g$ $a_y = 0$ $a_z = -1\times g$	9.63	1	$U_x = 0 \div 0.034$ $U_y = -0.01 \div 0.31$ $U_z = -0.017 \div 0$
6	$a_x = -5\times g$ $a_y = 0$ $a_z = -1\times g$	12.63	1	$U_x = -0.031 \div 0$ $U_y = -0.01 \div 0.31$ $U_z = -0.017 \div 0$
7	Pressure *P*=1900 Pa	39.2	27.3	$U_x = -0.027 \div 0.027$ $U_y = -0.04 \div 4.3$ $U_z = -0.3 \div 0.34$
8	Pressure *P*=-1900 Pa	39.2	27.8	$U_x = -0.027 \div 0.027$ $U_y = -4.3 \div 0.037$ $U_z = -0.3 \div 0.34$

The window frame and the brackets were made of aluminium alloy 6061 (Al-Mg-Si) having a composition specified in PN-EN 573-1:2006. The alloy is characterised by good mechanical properties and weldability, yet its specific properties largely depend on the state of hardening. Other important features include good treatability and corrosion to resistance.

The window was provided with double glazing composed of two TSG panes separated with a spacer around the entire circumference. Calculations involved a 4 mm thick single hardened TSG windowpane. TSG panes are characterised by good mechanical properties, i.e. deflection strength of 200 MPa and a tensile strength of approximately 50 MPa.

The adhesive joint was made using a Sikaflex 265 1-component polyurethane adhesive [3], a flexible structural adhesive for fixing windowpanes in busses, lorries, cars and railway vehicles. The tensile strength of adhesive joints amounts to approximately 6 MPa, whereas their shear strength amounts to 4.5 MPa. Advantages of the adhesive include odourlessness, resistance to weather and UV radiation.

In accordance with PN-EN 12663: 2010 [8], where a structure is verified numerically, the value of safety coefficient for each load should amount to 1.15. Therefore, allowed stresses for the above named aluminium alloy are the following [8]:

$$\sigma_{dop} = \frac{R_{e\,Al}}{1,15} \tag{6}$$

$$\sigma_{dop} = \frac{170}{1,15} = 147\ \text{Mpa} \tag{7}$$

where $R_{e\,Al}$ – yield point of the aluminim alloy.

According to UIC-566, when a window is subjected to a load, the permissible deflection in the centre of a windowpane cannot exceed the values presented in Table 6. Tables 7 and 8 present adhesive bond load cases for a single 4 mm thick TSG windowpane.

FEM Analysis of a Selected Adhesive Joint

The maximum stresses and strains of a windowpane depending on loads are presented in Table 9. The permissible stresses specified for the base material, i.e. aluminium alloy 6061 (147 MPa) and the permissible maximum deflection of a 10 mm thick windowpane were not exceeded in any case. Figures 9-12 present a graphic visualisation of results obtained for cases concerning the exposure to a pressure of 1900 Pa, for which the maximum values of stresses and strains were observed.

Conclusions

The performed FEM analysis of the adhesive joint of the windowpane with aluminium brackets justified the following conclusions:

- For load cases no. 7 and 8, i.e. when the windowpane was exposed to a pressure of 1900 Pa towards the inside of the vehicle and towards the outside, it was possible to observe the maximum values of strains, reduced von Misses stresses and principal stresses:
  - maximum deflection of a glass pane amounted to 4.3 mm (Table 9),
  - greatest reduced von Misses stresses were present in the corner of the aluminium bracket and amounted to 39.2 MPa (Table 9),
  - maximum principal stresses amounted to 27.8 MPa in areas close to the fastening (Table 9).
- FEM-based strength-related calculations offer significant time and cost savings, yet it is advisable to verify calculations experimentally. On the basis of FEM calculations, it was not

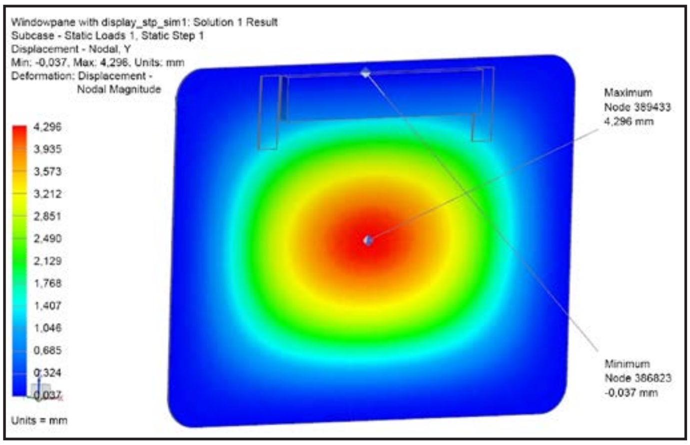


Fig. 9. Maximum deflection of the windowpane

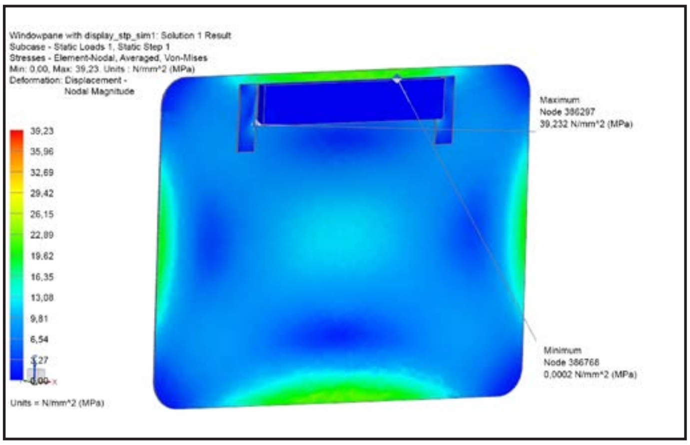


Fig. 10. Reduced von Misses stresses

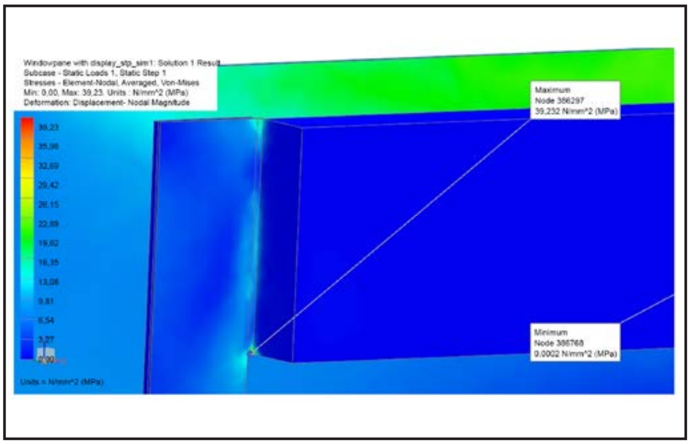


Fig. 11. Area of the greatest concentration of stresses

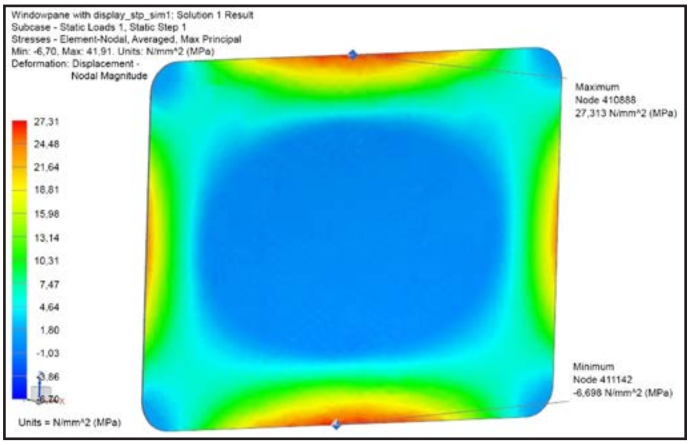


Fig. 12. Principal stresses in the windowpane, inside

possible to refer to ageing tests. Additional tests taking into consideration the ageing of the adhesive were not possible in the version of the software application used in the tests.

- None of the cases revealed the exceeding of permissible stresses and strains in the adhesive joint. The adhesive joint transmitted stresses affecting the windowpane on the display mounted inside.

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