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PAWEŁ KISIEL*, ZBIGNIEW MIKULSKI*, ARKADIUSZ KWIECIEŃ*, PIOTR FIELEK*

REDUCTION OF DISPLACEMENT IN CONCRETE TRAM TRACKS UNDER ENVIRONMENTAL EFFECTS USING POLYMER FLEXIBLE JOINT TECHNOLOGY

REDUKCJA PRZEMIESZCZEŃ BETONOWEJ NAWIERZCHNI TRAMWAJOWEJ WYWOŁANYCH WPŁYWAMI ŚRODOWISKOWYMI ZA POMOCĄ POLIMEROWEGO ZŁĄCZA PODATNEGO

A b s t r a c t

Large displacements caused by temperature loads are a significant problem in the design and operation of concrete tram surfaces. There is frequently observed damage to expansion joints between slabs induced by high displacements as well as aging processes. As a result, water penetrates through cracked expansion joints causing structural degradation. Tests performed in situ indicate that polymer flexible joints may be used as concrete slab connections in concrete tram surfaces. Besides sealing, this technology allows transferring loads within large deformation states, additionally, rotation angles of slab edges are decreased, reducing the risk of damage to connections. This work analyzes the structural behaviour of a section of a tram surface connected by polymer flexible joint technology. A FEM numerical model in was constructed in Abaqus 6.12 with the analysis of thermal loads. This paper presents the analysis of deformation and stress distribution in structural elements, in cases of different constructional variants; the results are presented and conclusions are drawn.

Keywords: concrete slab, polymer flexible joint, temperature load, tram surface

S t r e s z c z e n i e

Duże przemieszczenia wywołane obciążeniami termicznymi stanowią znaczny problem przy projektowaniu i realizacji nawierzchni betonowych. W konstrukcjach tych często obserwuje się występowanie uszkodzeń dylatacji wywołanych dużymi przemieszczeniami i starzeniem się materiałów. W wyniku utraty szczelności połączenia może dojść do negatywnych skutków wywołanych penetracją wody pod konstrukcję. Pierwsze próbne aplikacje *in situ* Polimerowego Złącza Podatnego wykazały, że może być ono stosowane jako dylatacja w nawierzchniach betonowych. Dzięki swoim właściwościom złącze nie tylko efektywnie uszczelnia nawierzchnie betonowe, ale również przenosi obciążenia przy dużych przemieszczeniach. W rezultacie następuje redukcja kąta obrotu obrzeży płyt, co znacznie zmniejsza ryzyko uszkodzenia połączenia. Artykuł zawiera analizę pracy mechanicznej typowego torowiska tramwajowego, w którym zastosowano Polimerowe Złącze Podatne. Wykonano model numeryczny z obciążeniem termicznym w programie Abaqus 6.12. W pracy zaprezentowano szereg wyników analiz wykonanych w różnych wariantach konstrukcyjnych oraz zaprezentowano wnioski.

Słowa kluczowe: nawierzchnia betonowa, obciążenie termiczne, polimerowe złącze podatne, nawierzchnia tramwajowa

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* Institute of Structural Mechanics, Cracow University of Technology, Poland.

1. Introduction

Polymer flexible joint (PFJ) technology is an innovative approach for structural connections. One of the most important features of the technology is the ability to transfer loads in large deformation states. Large deformations in concrete pavements are an inevitable problem due to high level of loads caused by temperature. Traditionally made expansion joints often encounter damage due to environmental and mechanical effects. Large dislocations may force the filling (bitumes) to squeeze outside the expansion joint. Unfortunately, due to the filling's low adhesion to concrete, detachment of the filling material can be observed (Fig. 1). Environmental cycles can lead to the filling leaking; as a result, water penetration into expansion joint and next under concrete structures can be commonly observed, this causes further destruction through a hydrodynamic effect [1, 2].

Fig. 1. Damaged expansion gap filled with bitumen

In-situ tests show that PFJ can be used in concrete slab connections. The joint has been used in surface repair since 2007 and it has been working properly for 7 years, until reconstruction of the concrete pavement. It has been shown that joints' hyper-elastic behaviour causes displacement reduction, due to its ability to transfer loads [1, 3]. Consequently, the rotation angle of the slab's edges is reduced, this decreases the amount of filling (bitumes) being squeezed out of the expansion joint. PZP usage can also positively influence stresses coming from loads from vehicle passes due to dislocation reduction in the middle of the slabs.

This work is the numerical analysis of a typical concrete precast tram surface. The aim of this paper is to examine the influence of PFJ application on displacement reduction and stress distribution change in a section of tram track support under temperature loads.

2. Research methodology

2.1. Analyzed structure's description

A set of numerical analyses were performed in Abaqus 6.12 using the finite element method. In this investigation, a section of tram surface with a typical construction and consisting of 7 precast slabs is analyzed. The analyzed construction variant was applied in Krakow with expansion gaps filled with bitumen – this was damaged after a couple of years of operation. In this research, 6 constructional and load variants are analyzed, as shown in Tab. 1.

Table 1

List of analyzed numerical variants

	Type of construction	PFJ width	Temperature difference
Variant 1	without PFJ	-	55°C
Variant 2	with PFJ	2 cm	55°C
Variant 3	with PFJ	1 cm	55°C
Variant 4	with PFJ	3 cm	55°C
Variant 5	with PFJ	2 cm	40°C
Variant 6	with PFJ	2 cm	20°C

Variant 1 represents a construction with a typical expansion gap filled with bitumen. Variant 2 uses very similar parameters to Variant 1, but has constructed PFJ in expansion joint. Comparison of results obtained for these two variants would indicate the influence of PFJ usage in place of traditional expansion joints.

The next analyzed series is represented by variants 2, 3 and 4. Analysis of these examples show the influence of PFJ thickness change on dislocations and stress distribution. In present in-situ experiments, it is most common to apply a PFJ thickness of 2 cm, but the optimal thickness has not been proven for various applications.

The influence of temperature load level on construction behaviour was analyzed in variants 2, 5 and 6. These cases show how displacement changes the load level in a mid-span of the slabs at different temperatures.

This work is an analysis of a typical tram track support in urban areas that allows car movement. Fig. 2 presents the visualization and cross-section of the analyzed structure. It consists of four slabs transferring tram loads and three slabs between them.

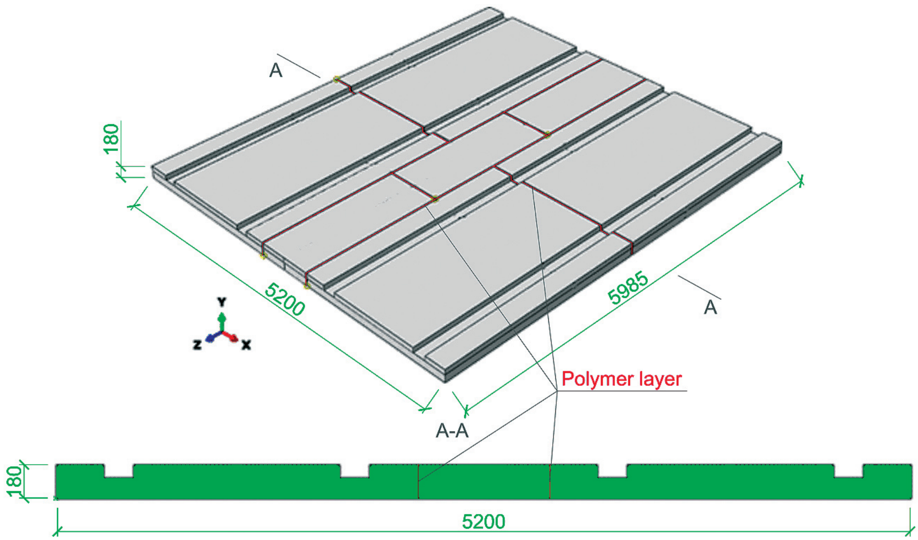

Fig. 2. Visualization of the structure and it's A-A cross-section, dimensions in [mm]

2.2. Numerical model description

Numerical analysis uses the finite element method analysis made in Abaqus 6.12. Three-dimensional elements are used to model concrete (type C3D8R) and polymer (C3D8H). Geometrical nonlinearity was considered due to large deformations in polymer material filling expansion joints. The elements mesh was dense in the joint zone. Contact with friction was set up as foundation for the slabs. With this solution, the slab can detach from its base during deformation. Material parameters for the concrete were assumed according to the Eurocode rules [4]. Numerical model visualization is presented in Fig. 3.

Boundary conditions set in Variant 1 allow the slabs to be freely lifted and rotated on a contact surface during deformation. The analysis was performed in two steps. Firstly, a heat flow analysis was made. A temperature of 60°C was applied at the upper surface of the construction, and 5°C at the bottom, based on measurements from previous research [1]. As a result, temperature distribution in each node has been obtained. Secondly, a static analysis was performed with the thermal load. A coefficient of thermal expansion for concrete of $1.2 \cdot 10^{-5}$ 1/°C [4] was assumed.

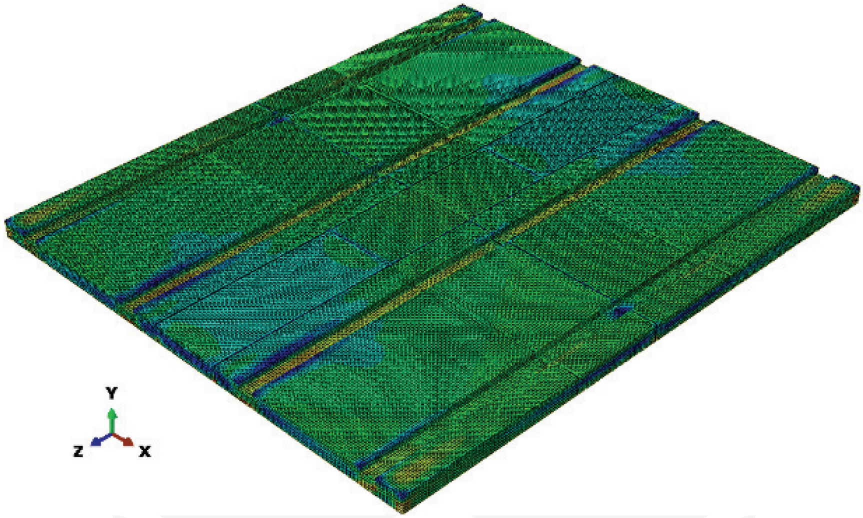

Fig. 3. Numerical model visualization

2.3. Material model of polymer

This analysis based on hyper-elastic Mooney-Rivlin model of polymer, according to the relationship:

$$U = C_{10}\left(\overline{I}_1 - 3\right) + C_{01}\left(\overline{I}_2 - 3\right) + \frac{1}{D_1}\left(J^{el} - 1\right)^2 \tag{1}$$

where U is the strain energy per unit of reference volume; C_{01} and D_1 are temperature-dependent material parameters; $\overline{I}_1$ and $\overline{I}_2$ are the first and second deviatoric strain invariants [5].

The material model uses a set of simplifications. Parameters: C_{10}, C_{01} were obtained in laboratory tests performed at room temperature, different from presented in the analyzed case. Additionally, the coefficient of thermal expansion for polymer was set as $1.56 \cdot 10^{-4}$ 1/°C after [6,7].

3. Results and discussion

A series of stress and displacement maps was obtained as a result of FEM calculations. In order to facilitate visual comparison, maps are shown at the same scale. It should be noted that deformation images are not at a 1:1 scale – they were resized 100 times in order to show the type of deformation of each slab.

3.1. PFJ application

Fig. 4 presents displacement maps for Variants 1 and 2. It can be noticed that for the variant with applied PFJ, the maximum displacement reduction is approximately 20%. The comparison of the two maps also shows a lower value of the angle of rotation of the slabs' edges (this can be noticed by smaller dislocations increments). This can by caused by mechanical properties of the PFJ. Fig. 5 presents a stress map comparison. It is clearly shown that in variant 1, the middle slab does not transfer any load in the analyzed cross-section. Continuing, the stress map for Variant 2 indicates mechanical cooperation of the middle slab. It visibly shows that the PFJ application positively influences stress distribution in the whole structure.

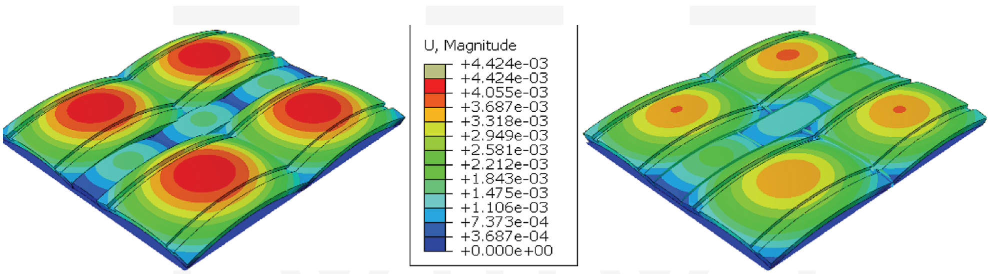

Fig. 4. Displacement maps for Variants 1 (on the left) and 2 (on the right) are at the same scale in [m]

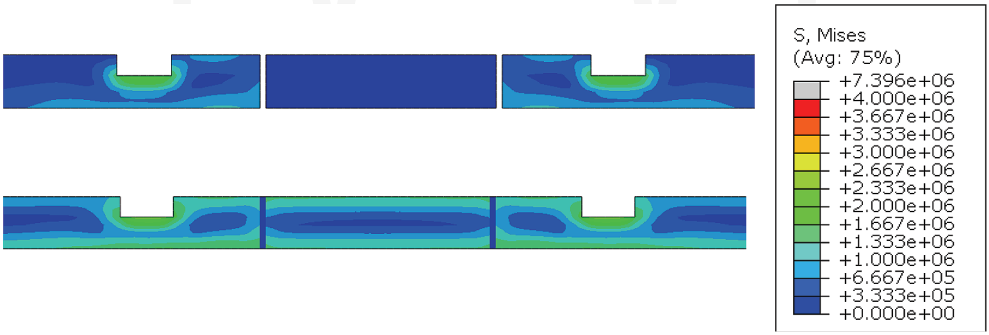

Fig. 5. Stress maps for Variants 1 (at the top) and 2 (at the bottom) at the same scale in [Pa] for middle section of A-A cross-sections

3.2. Thickness of PFJ

Displacement maps calculated for Variants 2, 3 and 4 are presented in Fig. 6. It can be noticed that the smallest values of displacement were obtained for variant 2. One can conclude that for particular design parameters (geometrical variant, temperature loads and stiffness of elements), a PFJ thickness of 2 cm is optimal. For variant 3 (thinnest PFJ of 1 cm), all the slabs react as a stiffly connected continuous structure – this can be observed in Fig. 6. Additionally, displacements calculated for variant 4 are larger than for variant 2. This can be caused by too low stiffness of the connection due to its large width. However, one can also notice that the maximum displacement calculated for this variant is 8% smaller than for Variant 1 which represents the structure with the expansion gap filled with bitumen.

Analysis of stress maps from Fig. 7 lead to the conclusion that stress levels in analyzed cross-section increase with a decrease of the thickness of the connection. In all variants, stresses are redistributed over all slabs.

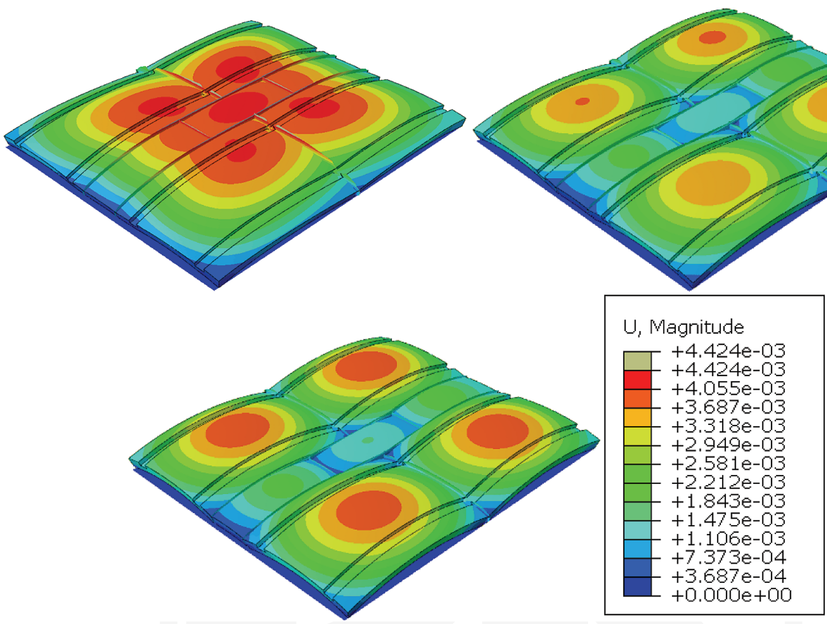

Fig. 6. Displacement maps for Variants 3 (in the upper left), 2 (in the upper right) and 4 (at the bottom) at the same scale in [m]

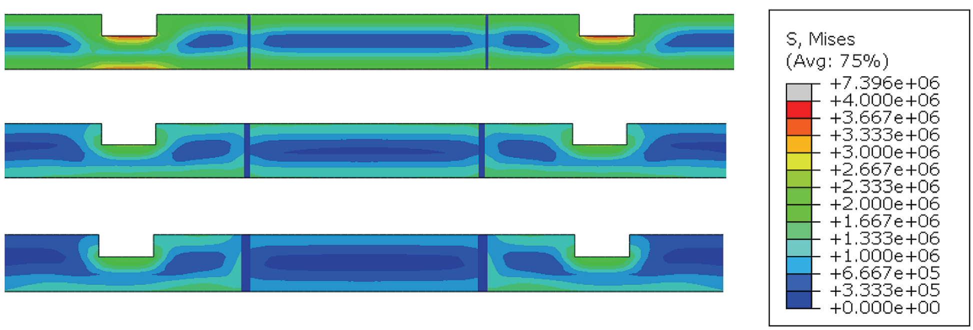

Fig. 7. Stress maps for variants 3 (at the top), 2 (in the middle) and 4 (at the bottom) in the same scale in [Pa] for the middle section of A-A cross-sections.

3.3. Level of temperature load

Fig. 8 presents dislocation maps calculated for variants 2, 5 and 6. The level of deformation decreases proportionally to the reduction in the temperature difference as expected. Changes of maximum displacement with the temperature difference are shown using a graph presented in Fig. 9. Stress maps for analyzed variants are shown in Fig. 10. Comparison leads to the conclusion that stress distributions in the analyzed cross-section are similar for various levels of thermal load and differ only in the stress value.

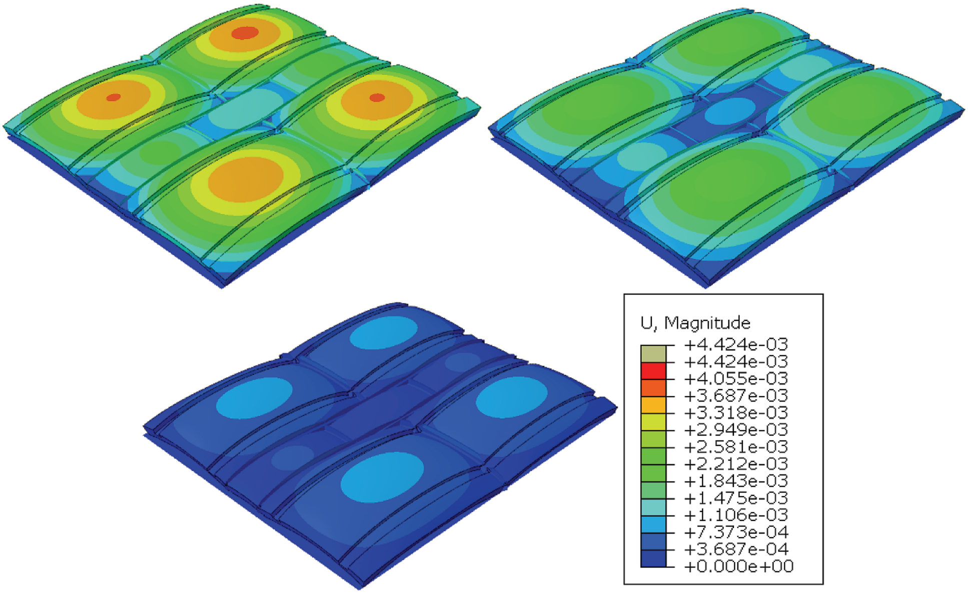

Fig. 8. Displacement maps for Variants 2 (in the upper left), 5 (in the upper right) and 6 (at the bottom) at the same scale in [m]

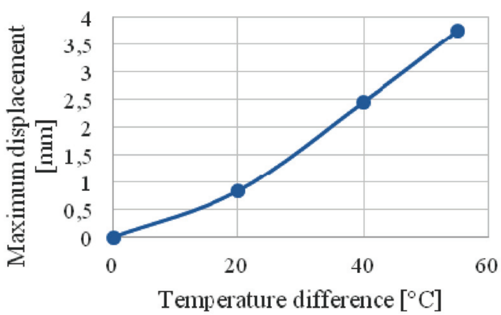

Fig. 9. Changes of maximum vertical displacement with the temperature difference of slabs with PFJ (for Variants 2, 5 and 6) in point M as indicated in Fig. 8

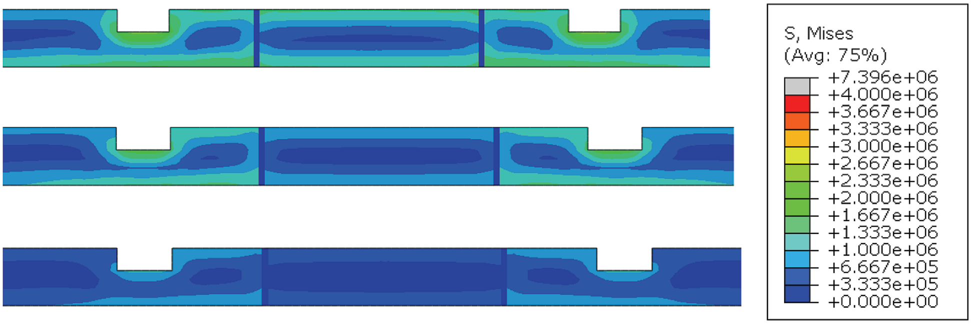

Fig. 10. Stress maps for Variants 2 (at the top), 5 (in the middle) and 6 (at the bottom) in the same scale in [Pa] for the middle section of A-A cross sections

4. Conclusions

Analysis of the presented results may lead to the following conclusions:

- PFJ application significantly reduces displacements in concrete tram track support made of precast slabs (19% in analyzed example);
- PFJ application introduces stresses in expansion joint zones, allowing for the transfer of loads;
- The thickness of PFJ has a significant influence on the behaviour of the system and its efficiency. For the analyzed example, the connection thickness of 2 cm provides a much better structural behaviour than a thickness of 1 cm or 3 cm;
- The dependence of the displacement reduction is approximately linearly proportional to the thermal load level;
- Due to the compression transfer, PFJ may protect slabs' edges from chipping resulting from large deformations.

This research will be continued by taking further load cases into account. Next, FEM models will be supplemented by loads coming from tram and car passes as well as from temperature uniform loads.

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