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Numerical-experimental analysis of durability of adhesive joints loaded in raised temperature conditions

K e y w o r d s

Strength of materials, adhesive joints, strength of adhesive joints, durability of adhesive joints.

S ł o w a k l u c z o w e

Wytrzymałość materiałów, połączenia klejowe, wytrzymałość połączeń klejowych, trwałość połączeń klejowych.

S u m m a r y

In the paper the strength of adhesive joints loaded in raised temperature conditions was researched. Considering the great difficulty with researching of long-term strength by experimental methods, numerical analysis was used to achieve this aim. According to experimental and numerical research, durability of adhesive cement Belzona 1111 was tested for the assumed conditions of experiment. There was proved that the degree of adhesive effort loaded over a long time depends on their strain, and theory of maximal strains can be usable for adhesive effort evaluation. There was affirmed that the character of cast the adhesive composites creeping curve gives a lot of essential information about adhesive joints' durability where they are used. Joints that are made from composites that are more susceptible to creeping are less durable.

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1. Introduction

The change in the adhesive joints' strength over time as well as their limited durability, particularly in raised temperature, is an essential problem for applying these solutions for constructors.

In undertaking the problems of durability of this type of connections in literature, there is lack of universal prognostic methods that could be applied in engineering practice.

The problems of durability of adhesively-bonded joints is also almost completely skipped by manufacturers of adhesive materials. This results mainly from time consuming task of durability inspections as well as their heavy expenses [1,2].

Two reasons of limited durability of adhesive joints are considered during analyses. The first is connected with natural process of in the time disintegration of cross-linked high-molecular composite structure that is the joint of adhesive connection (the change of cohesion strength) as well as the ageing processes on the adhesive/parent structure line (the change of adhesive strength). One point that should be emphasised is that ageing changes in natural conditions are perceptible after being measured in a month's time. An example of change in time of single lap joints strength, executed in accordance with standard PN-69/C-89300, aged in natural conditions and then loaded on shearing is shown in Fig. 1.

During inspections, the adhesive materials of an English manufacturer named Belzona 1111 and Unirep 3 as well as the national product named Chester Metal Super, based on epoxy resins, were used [3].

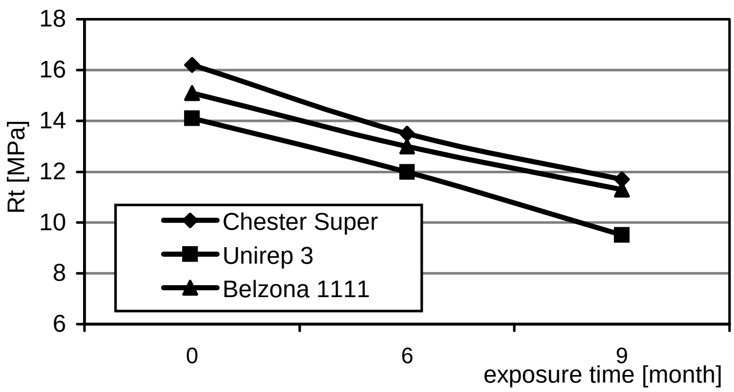

Fig. 1. Aged joints on shearing durability changes in natural conditions [1]
Rys. 1. Zmiana wytrzymałości na ścieranie złączy stalowych w naturalnych warunkach klimatycznych [1]

The mechanical proprieties of adhesive joints depend on the conditions they are exploited in, especially thermal conditions. Conducted in raised temperature up to 100°C, age investigations allow one to estimate the change of the temporary durability of joints made from adhesive materials – Fig. 2 [3].

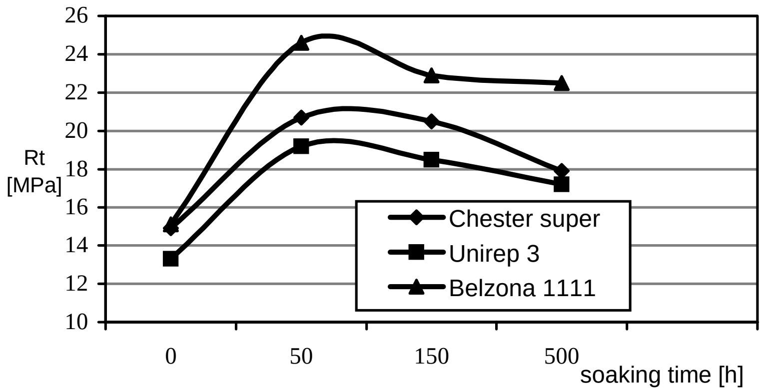

Fig. 2. Joints on shearing durability changes under the long-lasting influence of raised temperature (100°C) [3]
Rys. 2. Zmiana wytrzymałości na ścieranie złączy pddanych długotrwałemu oddziaływaniu podwyższonej temperatury (100°C) [3]

Noticeable growth of the temporary strength of joints was observed, particularly in first stage of investigations. In tests performed after 50 hours, over 50% growth of strength was noticed. It seems that the change of the strength of joints happened as a result of the curing of adhesive material in raised temperature. In tests performed after 500 hours time, the decrease of temporary strength was noticed. It seemed to be connected with adhesive progressive ageing process. Ageing inspections in natural conditions as well as raised temperature were performed for joints not under load.

Different mechanisms of failure exist in adhesive joints, which in conditions of raised temperature are subjected to long-lasting static loads simultaneously. In such conditions, the environment factors causing adhesive ageing have a smaller influence on the durability of such joints.

The rheological processes in the adhesive are becoming predominant. Adhesive as high-molecular material with spatially cross-linked structure in conditions of long-lasting load shows the propriety of viscoelastic substance (simultaneous occurrence of sticky and springy proprieties [4]). The incomplete cross-linking as a result of plastic nature causes occurrence of "free spaces ”(no cured or spatial cross-linking failures [5], where the bearing pads of macromolecules in liquid state appear (sticky liquid) during when macromolecules are in solid state (elastic solid)). The durability of connections begins, indeed depends, on phenomena characterising proprieties of hardened joint, among other things, include the occurrence of material stresses and strains time - dependence relating [1,4]. They contain, for instance, properties caused by constant stress strain changes (even if the stress is very small), which is the material creeping. Conducting of experimental analysis is the reliable method of the determination of the long-lasting durability of an adhesive joint [2]. These joints, however, with heavy costs, and even basic testing performance duration, seem to be unacceptable in engineering practice. At least because of complex stress in adhesively bonded joints, the analytic valuation of the long-lasting strength is also complicated. Therefore, it was decided to conduct the numeric analysis based on finite element method to recognise phenomena emerging in a long-lasting loaded joint, which can not be observed during experimental inspections.

2. Characteristic of numeric inspections

The numeric inspections concerning adhesive joints' durability requires, not only proper MES net generation, boundary conditions definitions as well as acceptance the definite type of adhesive–bonded joint strains in a function of time and load, but also qualification of adhesive physical proprieties [6,7]. During inspection, it was assumed that, in long lasting load conditions, the adhesive shows the propriety of lineally viscoelastic substance. To determine these adhesive properties, tetra parametric Bugers' substance model (Fig. 3) was used, because it represents all properties of viscoelastic substances in a qualitative way. This model is also implemented in NASTRAN for Windows - numeric calculations environment, which was used for numeric analyses.

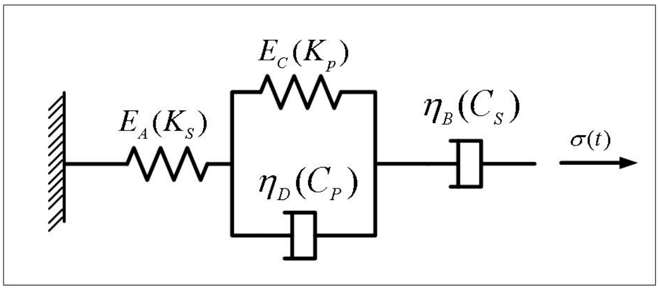

Fig. 3. Adhesive-bonded joint physical proprieties model, used for creeping phenomenon calculation in NASTRAN program
Rys. 3. Model właściwości fizycznych materiału spoiny klejowej występujący w programie NASTRAN do obliczania zjawiska pełzania

For such pattern of material coefficients, values E_A, E_C, η_B i η_D (in numeric calculations environment appointed K_S, K_P, C_S *i* C_P) should be declared. The size of strain depends on these coefficient values as well as load σ_o operating time t according to the following equation:

$$\varepsilon = \sigma_o\left(\frac{1}{E_A} + \frac{t}{\eta_B} + \frac{1}{E_C}\left(1 - \exp\left(-\frac{tE_C}{\eta_D}\right)\right)\right) \tag{1}$$

To assess these coefficient values, the methodology presented in study [1], based on adhesive treated as material, creep curve analysis was used. The experimentally determined the creep curve was divided into three sections (Fig. 4) – section of immediate strain – 1, section of transient creeping – 2, section of fixed creeping – 3.

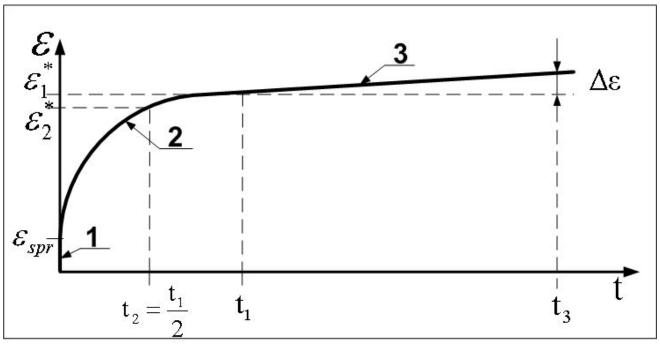

Fig. 4. Three characteristic ranges of creeping curve division
Rys. 4. Podział krzywej pełznania na trzy charakterystyczne zakresy

According to adopted methodology, the coefficient *Ks* value and elastic modulus value determined for initial part of stretching curve ($\sigma = \sigma(\varepsilon)$) are equal. In that connection, it can be determined in accordance with Hooke's law as follows:

$$K_S = E_A = \frac{\sigma}{\varepsilon_{spr}} \tag{2}$$

The coefficient C_S value and muffler viscosity (η_B) situated in series in adopted adhesive pattern are equal. Therefore, assuming fixed creeping in the third (3) range of the creep curve is constant ($d\varepsilon/dt = const$):

$$C_S = \eta_B = \sigma \frac{\Delta t}{\Delta \varepsilon} = \sigma \frac{t_3 - t_1}{\Delta \varepsilon} \quad (3)$$

remaining two coefficients values K_P (E_C) i C_P (η_D) were determined by solving a system of two equations, describing strain of Kelvin – Voight substance (muffler and spring joint in parallel), for time t_1 i $t_2 = 0{,}5t_1$:

$$K_P = E_C = \frac{(2\varepsilon_2 - \varepsilon_1)\sigma}{\varepsilon_2^2} \quad (4)$$

and

$$C_P = \eta_D = -\frac{\sigma \cdot t_1 (2\varepsilon_2 - \varepsilon_1)}{\varepsilon_2^2 \ln\left(1 - 2\frac{\varepsilon_1}{\varepsilon_2} + \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^2\right)} \quad (5)$$

It was considered also, that

$$\varepsilon_1 = \varepsilon_1^* - \varepsilon_{spr} - \frac{\sigma \cdot t_1}{C_S} \quad \text{and} \quad \varepsilon_2 = \varepsilon_2^* - \varepsilon_{spr} - \frac{\sigma \cdot t_2}{C_S} \quad (6)$$

Using experimentally determined Belzona 1111 composite creep curves (Fig. 5) as well as deduced relationships, K_s, K_p, C_s *and* C_p coefficients values indispensable to conduct numeric calculations were calculated. The results of calculations are shown in Table 1.

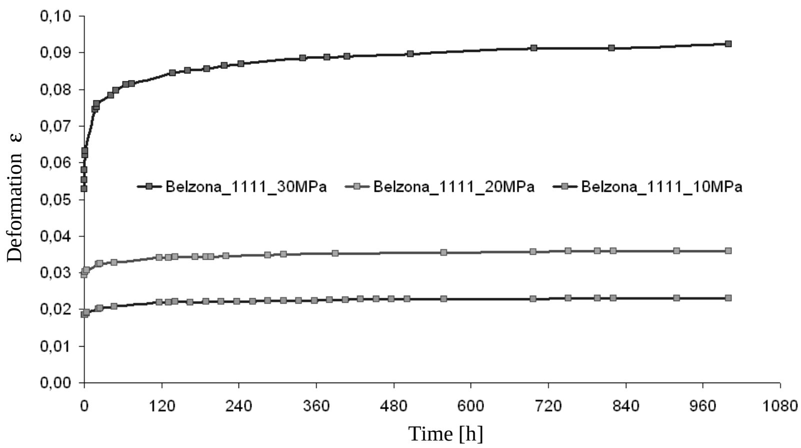

Fig. 5. Belzona 1111 composite creep curves formulated for different stresses at 60°C
Rys. 5. Krzywe pełzania kompozytu, Belzona 1111 uzyskane dla różnych naprężeń w temperaturze 60°C

Table 1. Belzona 1111 creeping coefficients values
Tabela 1. Wartości współczynnika pełzania dla kompozytu Belzona 1111

σ [MPa]	K_s [MPa]	C_s [MPa/s]	K_p [MPa]	C_p [MPa/s]
0	4545	$55\ 10^{10}$	2368	$50{,}43\ 10^{7}$
10		$58{,}16\ 10^{9}$		
20		$21{,}65\ 10^{9}$		
30		$10\ 10^{9}$		
40		$3\ 10^{9}$		
50		$0{,}2\ 10^{9}$		

Specific coefficients values let us to introduce to the model non-linear adhesive properties, thanks declaring creep coefficients in table form as following functions: Cp = f(σ), Kp = f(σ), Cs = f(σ) (Nonlinear Material Creep Properties → Tabular Model).

The skill of viscoelastic adhesive property modelling let us conduct numeric investigations of adhesive joints' long-lasting strength. During investigations, a numeric model, which came into being as a result of digitising the geometric model of adhesive joint overlapping specimen in Nastran for Windows program environment.

Individual component parts of joint were divided into HEXA type finite elements. This element has 8 nodes and 24 degrees of freedom (3 degrees of freedom in each node).

Due to computer program restrictions regarding the possible number of modelling elements as well as number nodes, and based on literature [8], with assumptions regarding the occurrence of a flat state of stress in overlapping adhesive joint, it allowed the consideration of the geometrical model slice of specimen about 2 mm in width.

In the adhesive layer, the essential region for conducting analysis, the increase of the nodes' net density was needed. Also, in the region of composite/adhesive element bond line, the adhesive element nodes net was concentrated gradually. Only the adhesive-bonded joint was divided into two layers of elements. Along adhesive length, every layer was modelled with 50 elements, whereas in width with 5 elements.

For digitising of metal elements, 1300 elements were used; whereas, for the adhesive-bonded joint, 500 elements were used. The discrete model of adhesive joint is shown in Fig. 6.

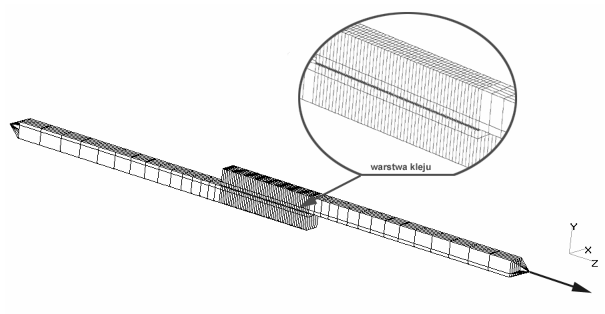

Fig. 6. Discrete model of shearing load overlapping adhesive joint
Rys. 6. Model dyskretny połączenia klejowego zakładkowego obciążenia na ścinanie

Because of the manner of conducting experimental investigations, where investigated specimens had an articulated joint, it was decided to create in discrete model close to real load and fastening conditions. That is why RIGID type elements were used.

In the analysed model of the overlapping joint, degrees of freedom (where it was supported) in independent nodes of two mentioned above RIGID type elements were taken.

Method and place of supporting is marked in Fig. 7.

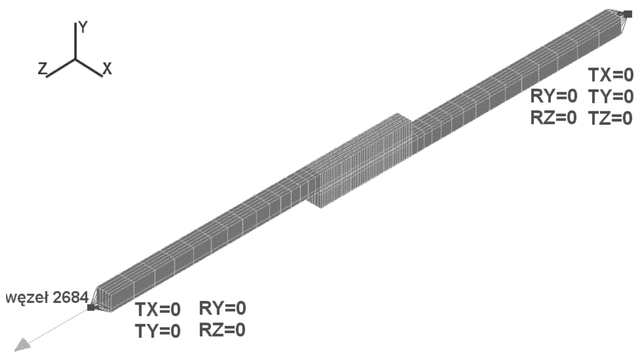

Fig. 7. Method and place of supporting and loading of adhesive joint
Rys. 7. Sposób i miejsce podparcia oraz dociążenia próbki klejowej

Overlapping model loading was modelled, thanks to imposing force causing normal stress in adhesively bonded metal elements. Force was imposed in node No 2684, which is on an axis of one of adhesively bonded metal elements (Fig. 6). The Belzona 1111 composite adhesive elasticity module value of E = = 4545MPa - was accepted to analysis. For bonded elements, elasticity module with a value E = 72000MPa was taken.

Long-lasting investigations were modelled in the program, thanks to imposing a two-staged load according to the scheme presented in Fig. 8.

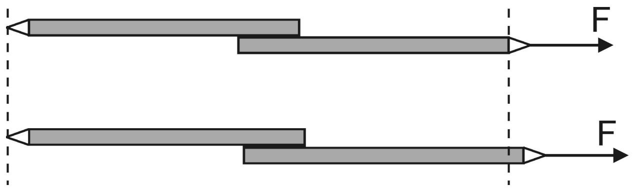

Fig. 8. Scheme of the two-staged load of overlapping specimen
Rys. 8. Schemat dwustopniowy obciążenia próbki zakładkowej

The first stage simulated a moment of a force applied to the specimen, and the force was applied to node No 2684, and then a load of Static Load for Non-linear Analysis category was imposed. The second one simulated a continuous load. It was executed by applying the same value of force to node No 2684 and declaring load of Creep Load for Non-linear Analysis category. Operating load time was also declared by the specific number of time steps. The proper time division of load during the following time steps guaranteed getting indirect outcome collections, which were then used in the analysis of received results.

Considerably smaller loads than causing damaging stresses were accepted during long-lasting adhesive joint strength analysis. These loads were at about 25% of the damaging load level; thus, it generated normal positive stresses at 15MPa in bonded elements.

3. Numeric and experimental investigations

Stress pattern, as well as strain, in overlapping adhesive joint analysis was made during numeric investigations.

Assuming that a flat state of stress in adhesive-bonded joint exists for the evaluation of the stress pattern, as well as strain, it was appointed a middle group of adhesive elements in one layer of glue (Fig. 9).

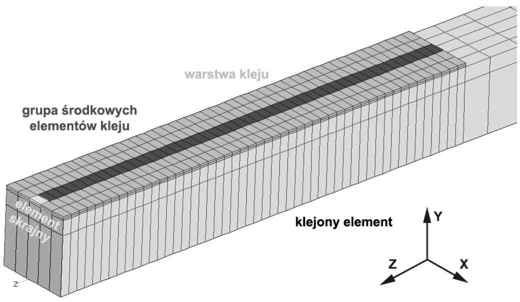

Fig. 9. Overlapping joint numeric model with the middle elements group and extreme element marked
Rys. 9. Numeryczny model połączenia zakładkowego z zaznaczoną grupą środkowych elementów spoiny i elementów skrajnych

The following material data were assumed for numeric analysis:

1. For glued elements: $\nu = 0.3$; $E = 7.2*10^4$ MPa.
2. For Belzona 1111 adhesive composite: $\nu = 0.35$; $E = K_S = 4.545*10^3$.

Creep coefficient values: K_P, C_P, C_S – taken from Table 1.

Modelled load in all cases was in accordance with accepted assumptions, i.e. two-staged load (constant force P causing normal positive stresses at 15 Mpa in joined elements).

To observe changes in the adhesive-bonded joint, we proceeded in assumed a time interval; it was necessary to determine stresses and strains for indirect time. It was assumed that numeric analysis would be conducted at the time of imposing load (t = 0) and at time 6, 60, 100, 120 hours. For simulation above the 120h, time loss of stability was observed. It appeared as physically unfounded cyclic changes of stresses in the time function.

Selected results of numeric investigations are presented in Figs. 10…13.

Taking the results of investigations shown in Figs. 9....12 into consideration, one can see that the stress pattern as well as strain pattern in adhesive-bonded joints in every investigated time interval is non-uniform. Little changes of shearing stresses τ_{zy} in the adhesive along overlap were also observed. At overlap ends, shearing stresses were reduced while, in the middle part of adhesive, they increased as time went on. It seems that the shearing stresses' patterns have the largest influence on maximal principal stresses, which change at adhesive ends only in the time function. Stress condition components – shearing stresses τ_{zx} i τ_{xy} have zero value.

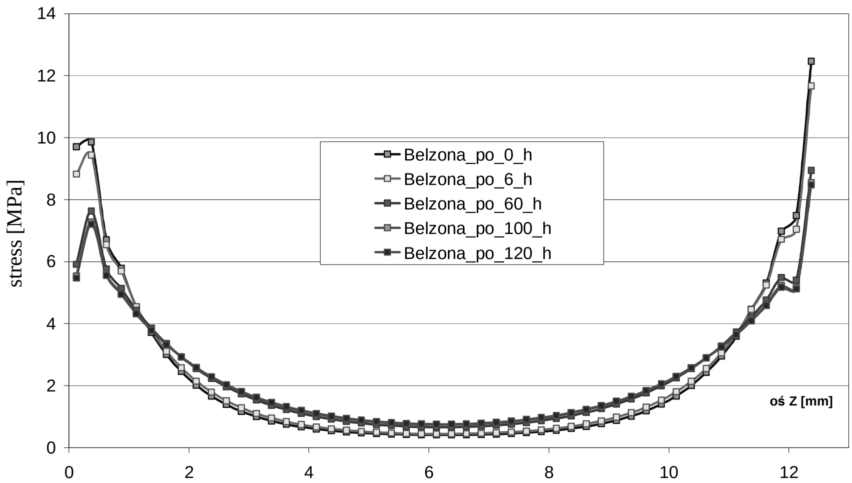

Fig.10. Shearing stresses (τzy) along adhesive joint change in time
Rys. 10. Zmiana w czasie naprężeń statycznych (τzy) wzdłuż połączenia adhezyjnego

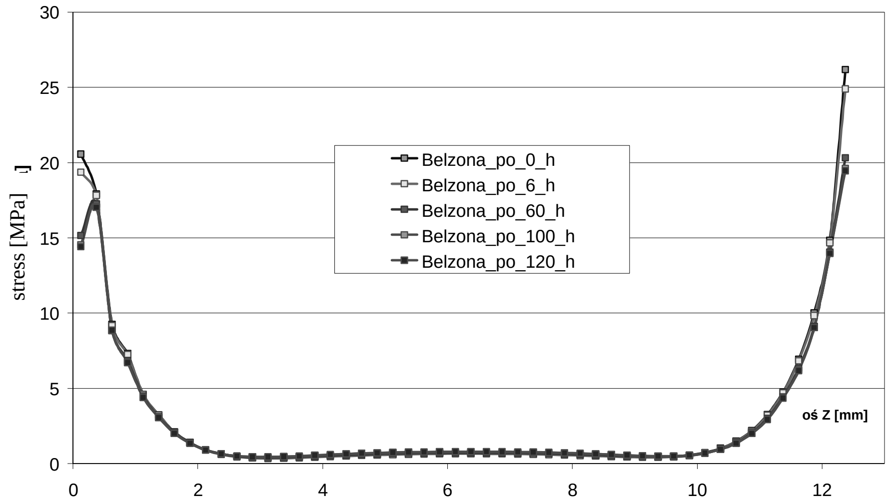

Fig.11. Critical main stresses along adhesive joint for Belzona 111 change in time
Rys. 11. Zmiana w czasie maksymalnych naprężeń głównych wzdłuż połączenia adhezyjnego dla Behona 1111

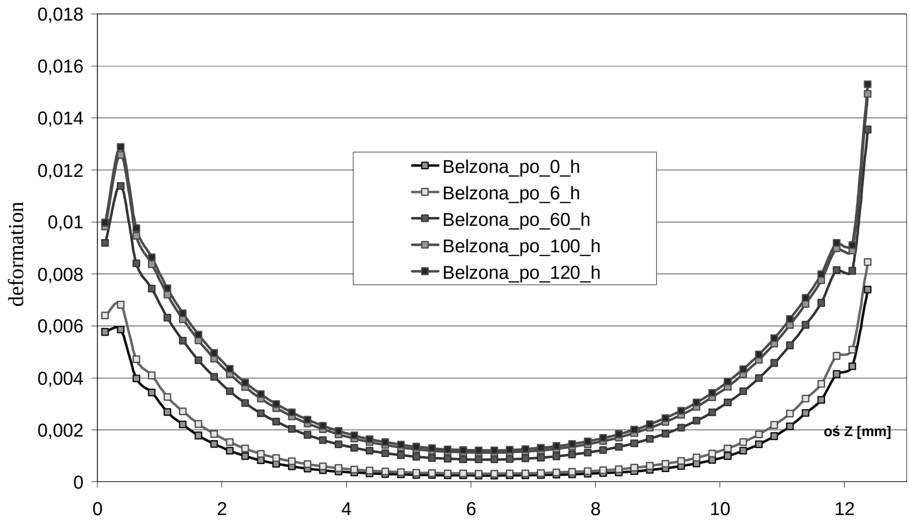

Fig.12. Non-dilatational strain (γzy) along adhesive joint for Belzona 111 change in time
Rys. 12. Zmiana w czasie odkształceń postaciowych (γzy) wzdłuż połączenia adhezyjnego dla Behona 1111

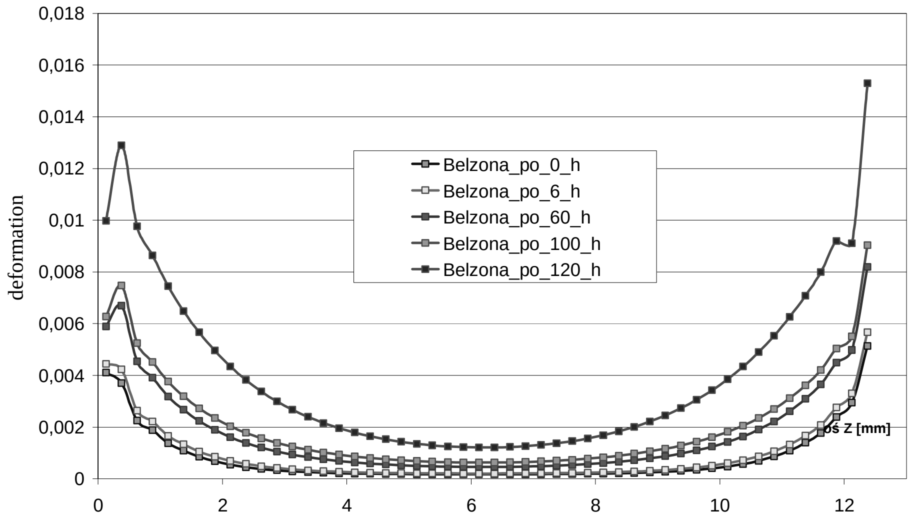

Fig. 13. Critical main strain along adhesive joint for Belzona 111 change in time
Rys. 13. Zmiana w czasie maksymalnych odkształceń głównych wzdłuż połączenia adhezyjnego dla Behona 1111

In case of strains, continuous growth of non-dilatational strains, as well as principal strains, can be observed. Strain increases along the adhesive-bonded joints are non-uniform. Strain increase is more intensive at adhesive ends than in the middle due to the larger stress level there. It should be noticed that, in comparison with stresses, strain depends on time definitely. Less growth values of maximal principal strains are in simulated time up to 100 hours. After 100 hours, such strain growth is more intensive.

Numeric investigations results obtained in which Belzona 111 properties were assigned to adhesive model were compared with numeric investigation results that were conducted for the adhesive model with Epidian 57 composite properties. Epidian 57 is a composite that is similar to Belzona 111, base on epoxy resin; however, it is not a physically modified product (Belzona 111 – a physically modified composite with metallic filler). Numeric investigation results for the adhesive model – Epidian 57 are presented in the study [1]. Maximum, principal strains, Belzona 111 and Epidian 57 adhesives, at time of imposing load and after 120 h are presented in Fig. 14.

A comparison of strains existing in these two adhesive models shows that adhesives made from Belzona 1111 are less susceptible to strains. It seems that adhesive–bonded joints where this composite was used should have higher durability, this was experimentally tested conducting additional investigations.

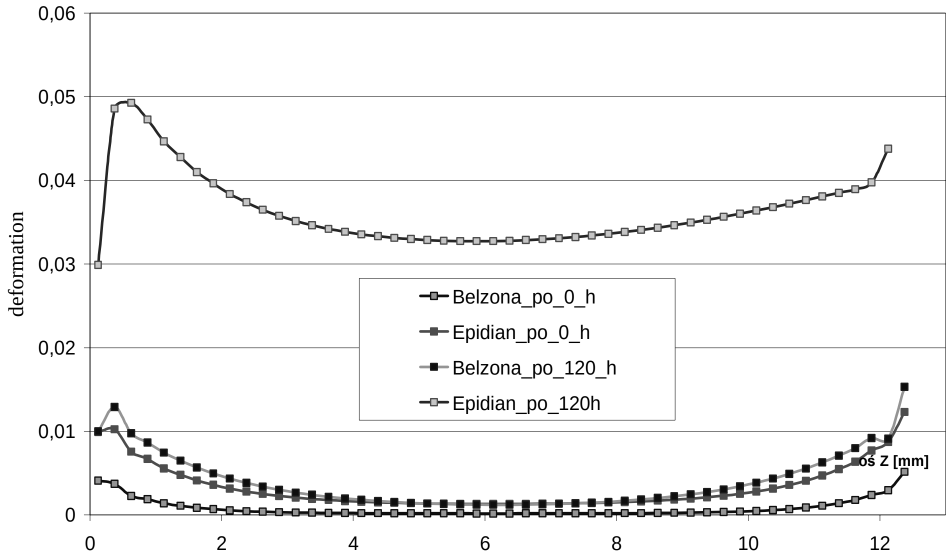

Fig. 14. Maximal principal strains change of time, along adhesive–bonded joint for two adhesive models (Epidian 57 and Belzona 111) at time of imposing load and after 120 h simulated time

Rys. 14. Zmiana w czasie maksymalnych odkształceń głównych wzdłuż połączenia adhezyjnego dwóch modeli spoiny (Epidian 57 i Belzona 111) w momencie przyłożenia obciążenia i po symulowanym czasie 120 h

During experiments, the time static durability of overlapping specimens made from Belzona 1111 and Epidian 57 was determined (2 batches of specimens were made). Specimens were loaded at 60% of damaging load level (structural adhesive-bonded joints are not normally loaded above a half of short-term strength level) [2]. Temporary strength of adhesive made from investigated composites was comparable: for Belzona 1111 - 2444±110N, for Epidian 57 - 2453±150N. Taking expected exploitation conditions of joints into consideration, tests were undertaken at 70^{O}C and 60^{O}C. Adhesively bonded specimens’ elements were made from PA7T4 aluminium alloy. Specimen element surfaces were prepared with the sandblasting method. Tests were restricted to 500 h, and results are presented in Fig. 15.

Joints made from Belzona 1111 withstood 500h test (after that time experiment was stopped), whereas specimens made from Epidian 57 were destroyed within few hours of the experiment.

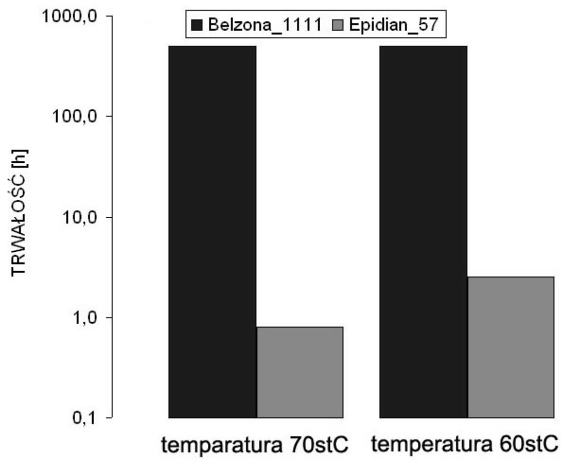

Fig.15. Durability of joints tested under load of 0,6Pn at $70^{O}C$ and $60^{O}C$
Rys. 15. Trwałość połączeń nadanych pod obciążeniem 0,6 PN w temperaturze 60°C i 70°C

Conclusions

1. Reduced strength of adhesive-bonded joints that was shown during experimental investigations confirmed that, on the joint projection stage, it is necessary to take the rheological properties of adhesive composites into consideration. Short-term strength can not be the only criteria of composite usability when serious structures are created.
2. Viscoelastic properties of adhesive–bonded joints, even those that were made using physically as well as chemically modified composites (e.g. Belzona 1111), have to be considered while conducting the long-lasting strength and durability of adhesive–bonded joints analysis.
3. Analysis of the state of stress as well as strain of adhesive–bonded joints loaded over a long period of time shows that maximal stress in adhesive decreases while strain increases. It seems that degree of adhesive effort loaded over a long time depends from their strain, and the theory of maximal strains can be usable for adhesive effort evaluation.
4. Adhesive overlapping joints, because of their less strain growth (joints creep more slowly), should have better durability. As experiments show, this is true mainly for adhesive composites made (e.g. Epidian 57) from epoxy resin. However, they contain a series of metallic fillers that strengthen the durability of joints made from such composites.
5. The model of lineally viscoelastic substance was used during numeric investigations. The adhesive composites, depending on operating conditions (load level, temperature) and composite structure, can behave as a non-lineally viscoelastic substance. In case of using strongly non-lineally

viscoelastic composites, one should take these into consideration during numeric tests and accept another model.

6. The character of cast adhesive composites' creep curve gives a lot of essential information about adhesive the joints' durability they are used in. Joints that are made from composites that are more susceptible to creep are less durable.

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Numeryczno-eksperymentalna analiza trwałości połączeń adhezyjnych obciążonych w podwyższonej temperaturze

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

W pracy rozważono wytrzymałość połączeń klejowych obciążonych długotrwale w podwyższonych temperaturach. Ze względu na duże trudności w określaniu wytrzymałości długotrwałej metodami eksperymentalnymi, rozważono możliwość zastosowania do tego celu metod numerycznych. Na podstawie badań eksperymentalnych i numerycznych określono, dla założonych warunków eksperymentu, wytrzymałość długotrwałą kompozytu klejowego Belzona 1111. Dowiedziono, że o stopniu wytężenia spoiny klejowej w przypadku obciążeń długotrwałych, decydują przede wszystkim jej odkształcenia, a hipoteza maksymalnych odkształceń może być przydatna do oceny wytężenia spoin. Stwierdzono, iż charakter krzywej pełzania odlewanych tworzyw adhezyjnych, dostarcza istotnych informacji o trwałości połączeń uzyskanych z ich użyciem.