Hindawi
Advances in Materials Science and Engineering
Volume 2017, Article ID 5941086, 10 pages
https://doi.org/10.1155/2017/5941086

Research Article

Numerical Analysis of Impact Loading of Adhesive Joints

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Received 3 July 2017; Revised 28 September 2017; Accepted 18 October 2017; Published 13 December 2017

Academic Editor: Miguel Angel Torres

Due to small repeatability of results of impact strength of adhesive joints, particularly those performed on different test machines, the authors were inspired to conduct experimental and numerical research in this field. The investigation used the Block Shear Test. The authors compared impact strength of samples which were loaded in a normative and non-normative manner and also the dependence in impact strength with regard to the distance between the impactor's edge and the surface of the bonded joint. The numerical calculations were carried out in the program Ansys, using the Explicit Dynamics module. The authors proposed a way of modelling the impactor of the pendulum hammer. It was found that a change in the direction of applying the load to the sample and rotating the loaded sample piece in relation to the edge of the impactor results in a significant change in the Max Principal Stresses. Numerical investigations show that lower values of Max Principal Stresses occur in joints which are characterized by larger impact strength, determined experimentally. It was also noted that moving away the edge of the impactor from the surface of the adhesive joint increases normal stresses perpendicular to the surface of the joint.

1. Introduction

Adhesive connections are becoming increasingly used structural connections, in many cases replacing or supplementing traditional mechanical connections [1]. While the subject of static strength of adhesive bonds is quite well known and discussed in literature [2], the issue of impact strength of adhesive joints has been the subject of a smaller number of experiments or theoretical deliberations. Among the research methods described in the available literature, it is possible to distinguish three most commonly used methods:

(i) The Block Shear Test (BST) [3, 4]
(ii) The Impact Wedge Peel Test (IWPT) [5, 6]
(iii) The method of impact shear of lap samples loaded in tension [7–10]

The problems occurring during the investigation of impact strength of adhesive joints are associated with large discrepancies of research findings and their low repeatability on test machines manufactured by different producers [2, 11, 12]. Therefore, it is difficult to evaluate such results as well as using them in practice for the assessment of glued structure strength.

We made an attempt to carry out a numerical analysis of the Block Shear Test method (Figure 1).

We conducted an investigation of the Block Shear Test of such samples using different directions of the applying the load, and then we conducted a numerical analysis of both cases in order to find relationships between impact strength of the examined samples and the distribution of stress values in the joints. We also checked experimentally the effect of the distance between the impactor's edge and the bondline as well as a slight twisting of the hit sample surface against the edge of the impactor, upon impact strength and stresses in the joints.

2. Experimental Research

2.1. The Effect of the Strike Direction upon Impact Loading of Block Samples. The sample elements were made with steel

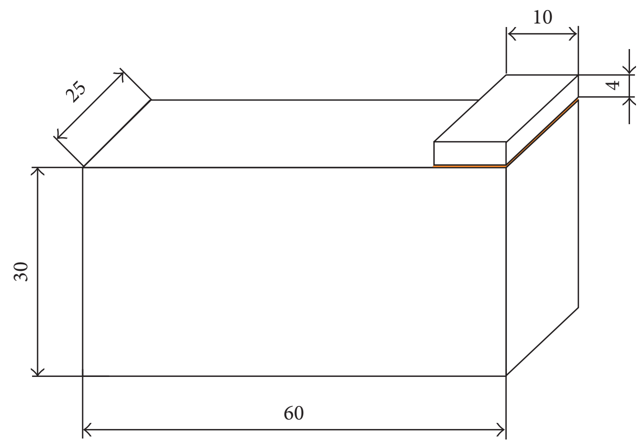

Figure 1: Dimensions of block samples.

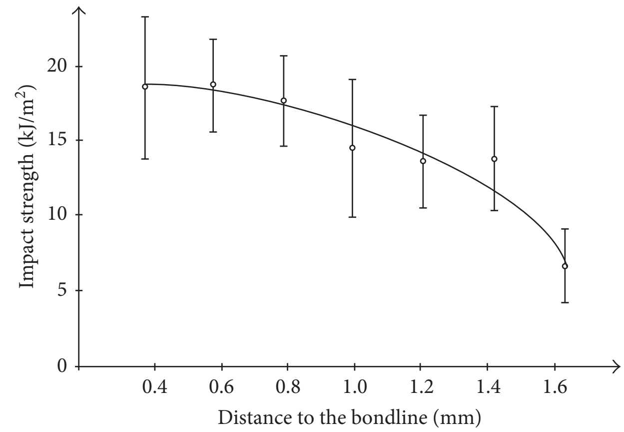

Figure 3: Impact strength in the function of the distance of applying the impact load to the bondline.

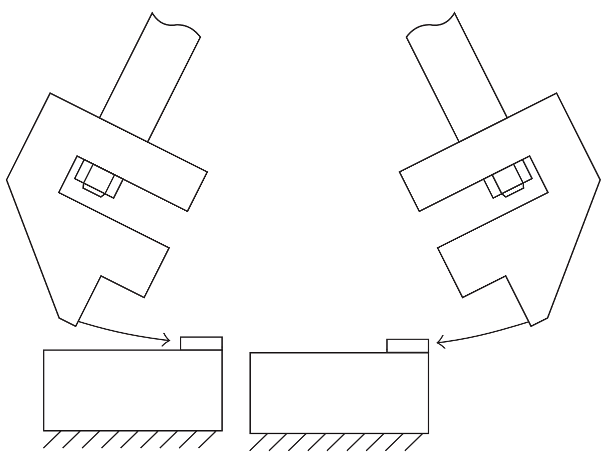

Figure 2: Diagram of research into impact loading. (a) Normative [4]; (b) nonnormative.

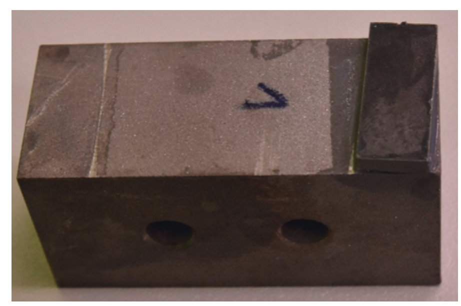

Figure 4: Sample with the upper element rotated at an angle of approximately 3.7°.

S235. The bonded surfaces were exposed to abrasive blasting with copper slag. We obtained surface roughness of mean arithmetic deviation of the profile from the mean line $Ra = 4.28\,\mu m$. After washing with petrol and drying, the elements of the samples were joined with Epidian 57/Z1 and hardened for 7 days at ambient temperature under the pressure of 40 kPa. The investigation was carried out on a special pendulum hammer whose maximum energy was equal to 15 J. The impactor struck the bonded plate at 0.8 mm over the bondline. The investigation was conducted for two directions of strikes (Figure 2). For each set of samples, we determined the mean value of impact strength as well as specifying a confidence interval by means of Student's t distribution for the confidence level of $1-\alpha = 0.95$. There was a significant difference in impact strength depending upon the direction of the pendulum hammer's strike. The impact strength of identically bonded samples during normative testing was $8.5 \pm 3.2\,kJ/m^2$ and $16.8\,kJ/m^2$ during nonnormative research.

2.2. Distance between the Edge of the Impactor and the Adhesive Joint. In the tests, we used a nonnormative direction of applying the impact of energy equal to 15 J. The distance between the edge of the impactor and the joint was determined by means of a feeler gauge. In the examination of the subsequent series, by means of special spacers, we either decreased or increased the distance of the lower edge of the pendulum hammer from the adhesive joint by 0.2 mm. For the sake of safety of the test device, the smallest distance of conducting the test equalled 0.4 mm. The largest distance in the testing equalled 1.6 mm. The findings of the experimental tests with marked confidence intervals are presented in Figure 3.

As a result of changes in the distance to the bondline, the measured impact strength also changed. The highest impact strength was characterized by adhesive joints, in which impact was applied the closest to the joint. Increasing the distance from the bondline resulted in lowering the registered impact strength of the joints. This phenomenon most possibly results from increasing the value of the applied moment, causing the tear-off of the front part of the upper part of the specimen. The results of the experimental studies were consistent with those presented by Adams and Harris [3]. In the range of 0.4 to 0.8 mm distance from the bondline, the impact strength

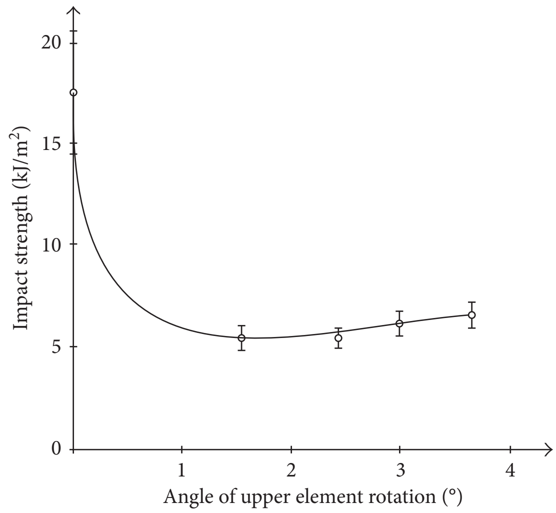

Figure 5: Impact strength of joints with a rotated spacer.

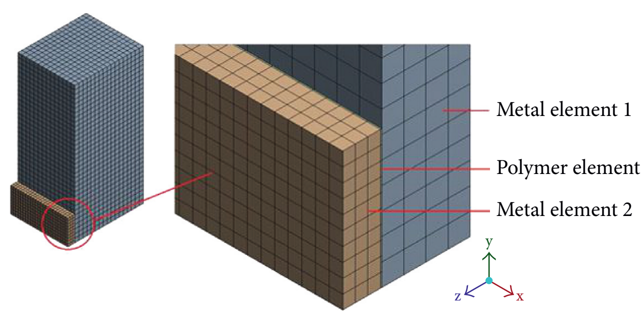

Figure 6: 3D model of the sample with a bonded cuboid element.

changes to a slight extent. The fall in impact strength is particularly noticeable after exceeding the distance of 1.0 mm. The lowest impact strength was characterized in joints where impact loads were applied at a distance of 1.6 mm away from the adhesive joint; the drop in impact strength equalled more than 65% with regard to adhesive joints, which were impact loaded at a distance of 0.4–0.8 mm from the joint.

2. 3. The Effect of Load Application at a Slight Angle. We examined joints in which the edges of the upper element were not parallel to the edge of the lower part of the sample (Figure 4).

When putting the samples together, the upper element in each sample was intentionally rotated at an angle of $0.5{-}4^{\circ} \pm 0.5^{\circ}$. The measurements of the obtained angles of element rotation were taken after curing the joints. The number of the bonded samples in each series varied (above 6 pieces), as it was impossible to precisely set the angles of the spacer while gluing. The values of the angles of rotation of the upper elements obtained in the selected series of the samples were as follows: 1.6, 2.4, 3.0, and 3.7°.

In the investigation, we used a nonnormative strike direction of the hammer with energy equal to 15 J. The course of the selected tests was recorded by means of a high-speed camera in order to determine whether the impactor rotates or twists around its axis, while striking the edge of the sample. The analysis of the records led to the conclusion that even with the slightest obtained angles of geometry irregularities of the sample, the impactor does not revolve about its axis; if the sample is glued improperly, the load is applied to one (more protruding towards the impactor) vertical edge of the upper element. The analysis of the video recording facilitated building an impact loading model for the sake of numerical investigations conducted in the next step. The findings of the experimental tests are presented in Figure 5.

The analysis of the chart (Figure 5) confirms a crucial influence of proper positioning of sample elements on the obtained research findings. The average impact strength of the control samples (bonded without rotation of the samples from each other) amounted to $17.85 \pm 3.21\,\mathrm{kJ/m^2}$ and the samples in which the upper element was rotated against the lower one by approximately $5.89 \pm 0.68\,\mathrm{kJ/m^2}$. The rotation of the upper element of the

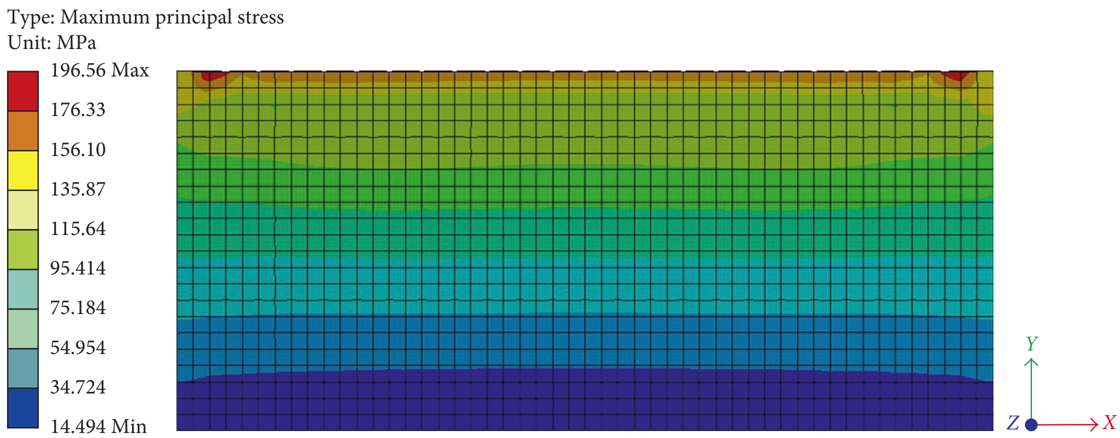

FIGURE 7: Map of Max Principal Stress distribution in the joint for the computational time equal to 0.0001 s, under normative loading (Figure 2(a)).

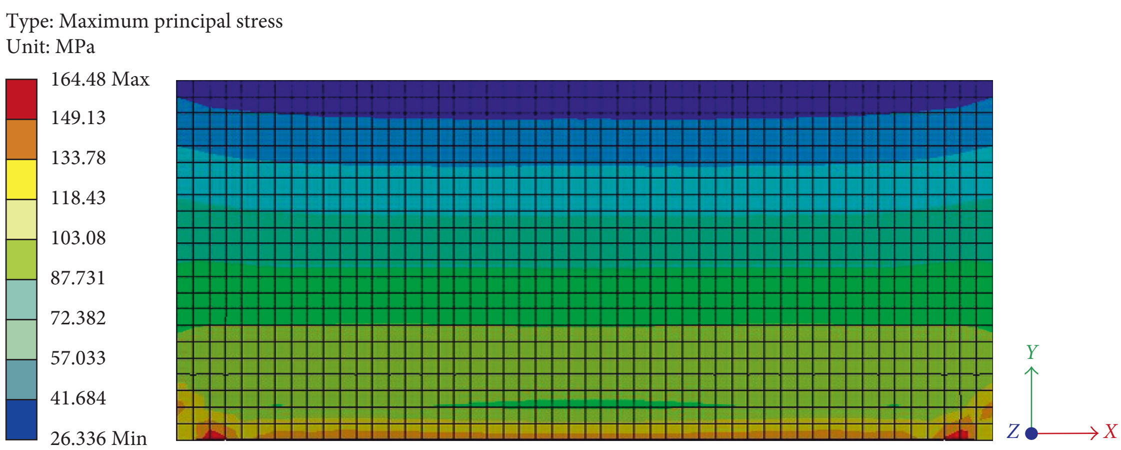

FIGURE 8: Map of Max Principal Stress distribution in the joint for the computational time equal to 0.0001 s, under nonnormative loading (Figure 2(b)).

sample against the lower element, even at a small angle, brings about a significant change in impact load conditions. The impact strength of samples, in which the elements are rotated, is over 65% lower with regard to the control samples.

3. Numerical Analyses

The calculations were carried out in the program Ansys, using the Explicit Dynamics module. We built a simple numerical model of the sample, which was divided into 8-node hexahedral finite elements (Figure 6), dedicated for dynamic computations (impact strength). In the modelling, we used the contact connection bonded-type Solid to Solid.

As we knew the mass of the pendulum hammer and its initial energy, it was possible to calculate the speed at which the impactor strikes the adhesive sample, that is, 2960 mm/s. In order to reflect the impactor's mass, we increased the density of the material to an extent that was declared for its manufacture so that it could be equal to the mass of the actual device. While declaring Young's modulus of the dropping tool as the one that corresponds to steel, it underwent excessive distortion, and therefore it obtained the properties of a rigid body. Eventually, the models of the tested samples were impact loaded with a dynamically rigid model (we used the rigid element) of the cuboid impactor with dimensions $5 \times 25 \times 3$ mm, with the speed of 2960 mm/s and the density of $9.2\,10^6$ kg/m^3, corresponding to the actual impact energy of the hammer used in the experiment (15 J). The calculations were carried out for two directions of the hammer and when the glued piece was slightly rotated towards the edge of the impactor. We compared the distributions of Max Principal Stresses in the joints for the same computational times, assuming that higher stress values should correspond to lower impact strength. Figures 7–9 present maps of distributions obtained in numerical calculations of the Max Principal Stresses calculations for the distance of 0.8 mm between the impactor's edge and the bondline.

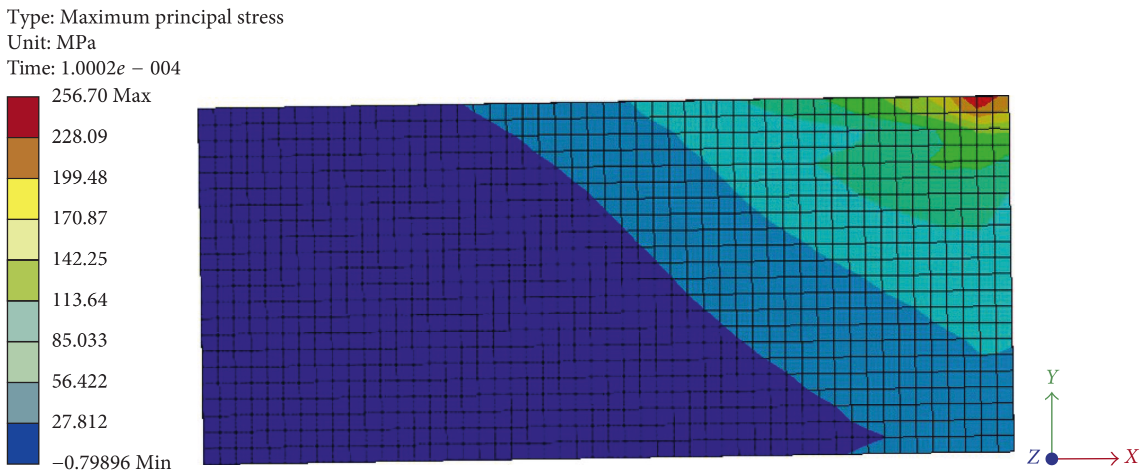

Figure 9: Map of Max Principal Stress distribution in the joint for the computational time equal to 0.0001 s, sample rotated against the impactor at angle of 3°.

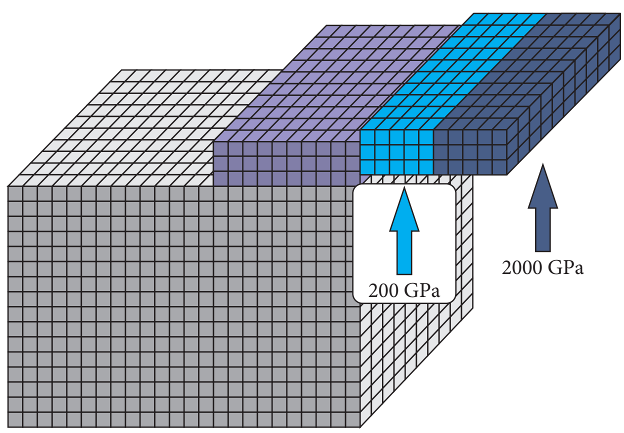

Figure 10: The impactor model consisting of two parts of varying stiffness.

It was confirmed that lower impact strength which results from the load direction or twisting of the element which is torn off by impact loading corresponds to greater stress values; however, we did not find quantitative correlation between impact strength and stresses.

In the further part of the numerical computations, the impactor was modelled as an element consisting of two parts—the piece striking directly into the sample was given steel properties; the other one had the modulus of elasticity higher, by one order of magnitude (2000 GPa), so as to ensure adequate stiffness of the striking element (Figure 10).

We analyzed the stress relationship in the joints, between the distance of the impactor's edge and the surface of the joint for the times corresponding to the maximum stress values (Figures 11 and 12).

The results of the analysis of the maximum stresses at the time of 2.4×10^{-4} s were not in line with the results of the experimental research. Therefore, the stress tensor component values were compared, corresponding to Max Principal Stresses, which equalled the tensile strength of Epidian 57/Z1 (~84 MPa) (Figures 13 and 14).

The calculations show that moving the edge of the impactor from the joint's surface results in an increase in normal stresses perpendicular to it (σ_y), which may be the cause of the decrease in impact strength of the tested connection. Due to the fact that stresses σ_y cause the adhesive joint to tear off, adhesive strength may then exert a decisive influence upon impact strength of the block connection in question while moving away the impactor's edge from the joint.

We also made an attempt to declare in the conducted dynamic calculations the model of damage related to the occurrence of Maximum Principal Stress in the adhesive (Max Tensile Stress 80 MPa and Max Shear Stress 80 MPa) (Figure 15).

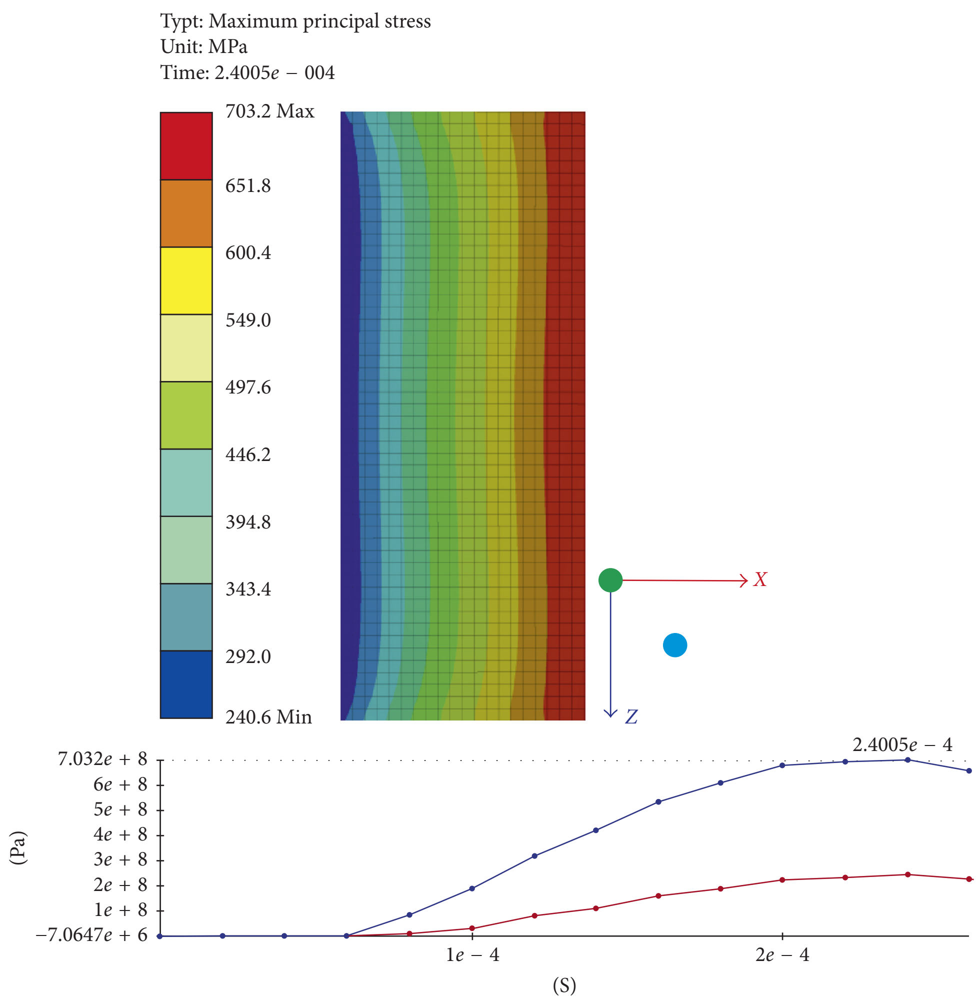

Figure 11: Distribution of Max Principal Stresses in the joint of a block sample (distance from the impactor's edge to the bondline equals 0.8 mm).

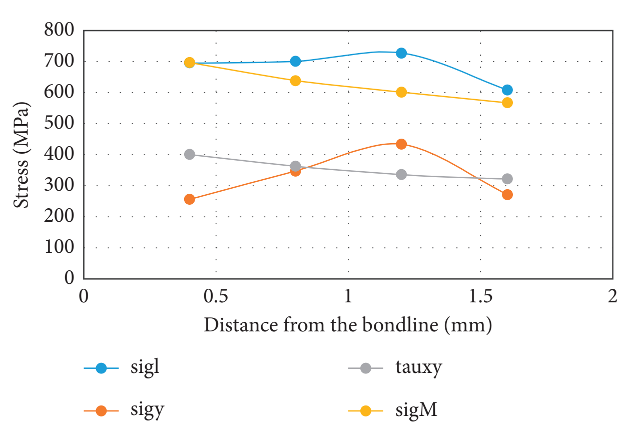

Figure 12: The dependence between maximum stresses in the joints and the distance of the impactor's edge to the bondline (sigI = Max Principal Stresses; sigy = normal stresses perpendicular to the surface of the joint; tauxy = tangential stresses in the direction of impact loading; sigM = von Mises stress).

However, these findings cannot be considered reliable, since numerical programs calculate reduced stresses in accordance with the von Mises hypothesis and destruction began at the site of maximum compressive stress. Adhesives, just like ceramic materials, though to a lesser extent, are characterized by higher compressive strength than tensile

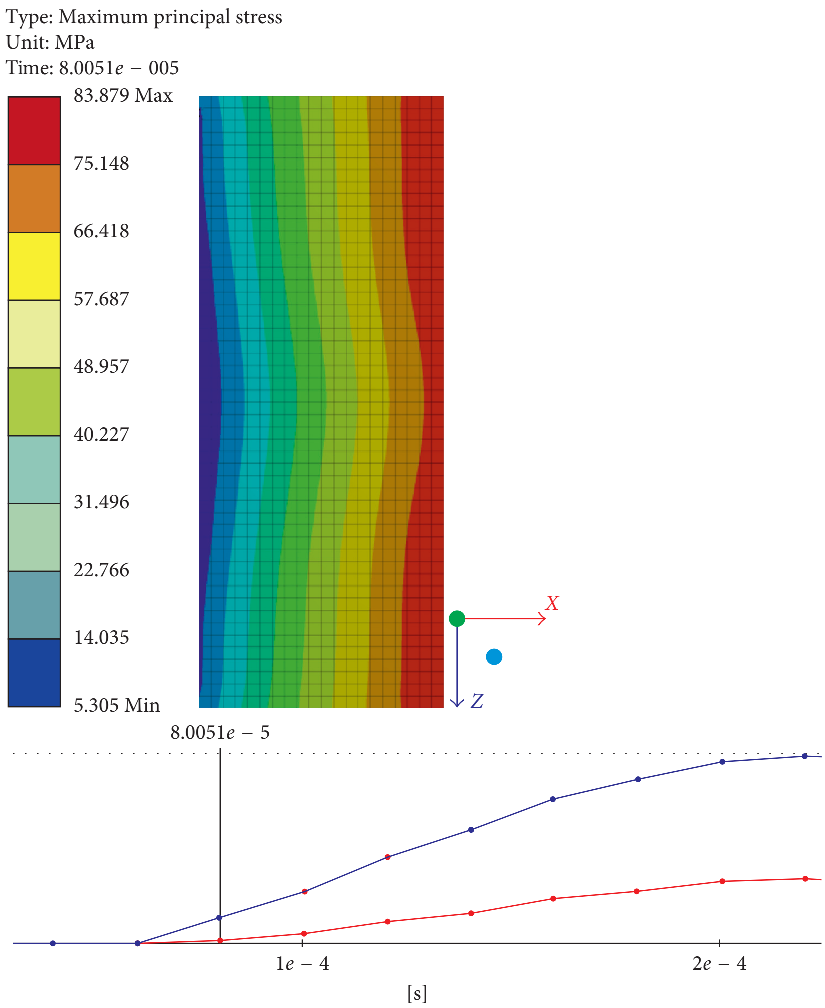

Figure 13: Distribution of Max Principal Stresses in the joint of the block sample when Max Principal Stresses reached tensile strength of the adhesive.

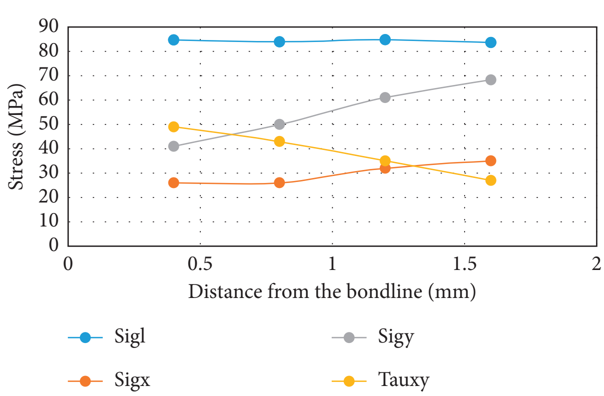

Figure 14: The dependence between maximum stresses in the joints and the distance of the impactor's edge to the bondline (SigI = Max Principal Stresses; Sigy = normal stresses perpendicular to the surface of the joint; Tauxy = tangential stresses in the direction of impact loading).

strength. For this reason, the program regards it as critical stresses (destructive) occurring in the rear part of the joint, where compressive stresses are dominant (Figure 16).

We also examined how the time histories of normal principal stresses in the joints of dynamically impact-loaded block samples change if the glued elements are made of different materials and the adhesive is characterized by various stiffness (Figure 17).

The conducted calculations proved that reducing the stiffness of both the joined elements and the adhesive itself leads to time extension, in which there are stresses in the joints as well as reductions of the value of Max Principal Stresses, which may cause increased impact strength.

4. Conclusions

(i) Changing the direction of applying the load to the block sample results in significant changes in the values of the obtained results of impact strength.

(ii) The numerical investigation shows that lower values of Max Principal Stresses occur in joints which are

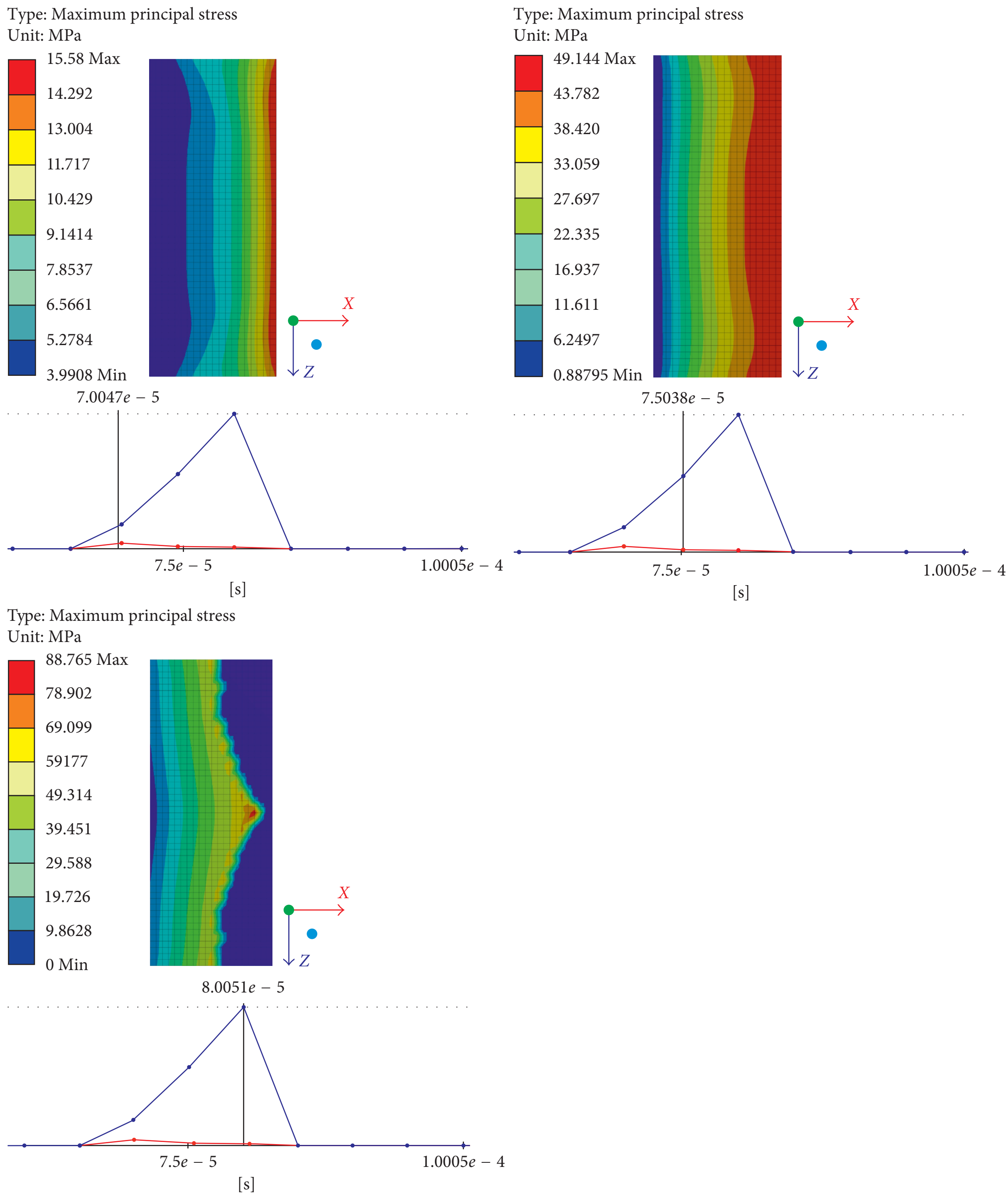

Figure 15: Changes in Max Principal Stress distributions in time, during dynamic impact loading of the block sample with declared adhesive tensile strength of 80 MPa.

characterized by larger impact strength, determined experimentally.

(iii) The drop in impact strength of block samples along with moving away the impactor's edge from the bondline is caused by a significant rise in normal stresses, perpendicular to its surface.

(iv) The findings of impact strength tests performed on the very same test station are characterized with large discrepancies, which is caused by the dimensional tolerance of particular samples and requires their modification in order to eliminate the likelihood of their uneven load.

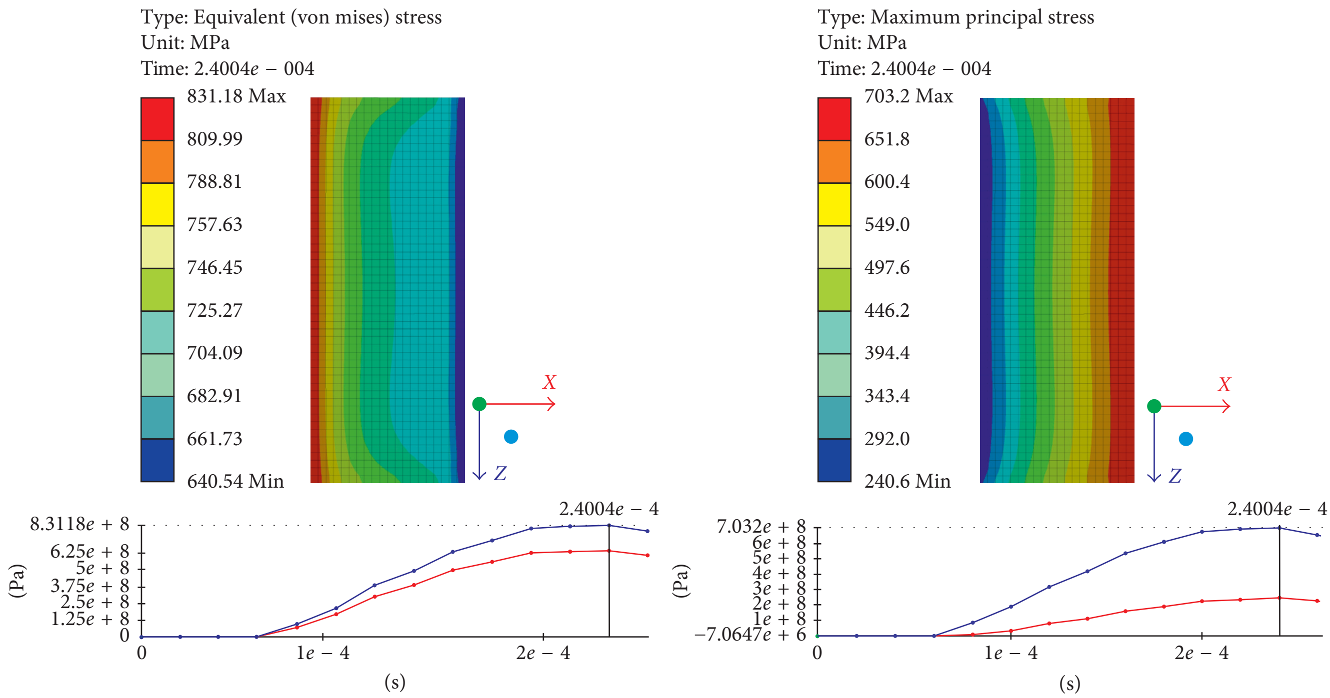

Figure 16: Distribution of reduced stresses (von Mises) in the joint of a block sample dynamically impact loaded (maximum stresses occur on the edge which is opposite to the impact-loaded one).

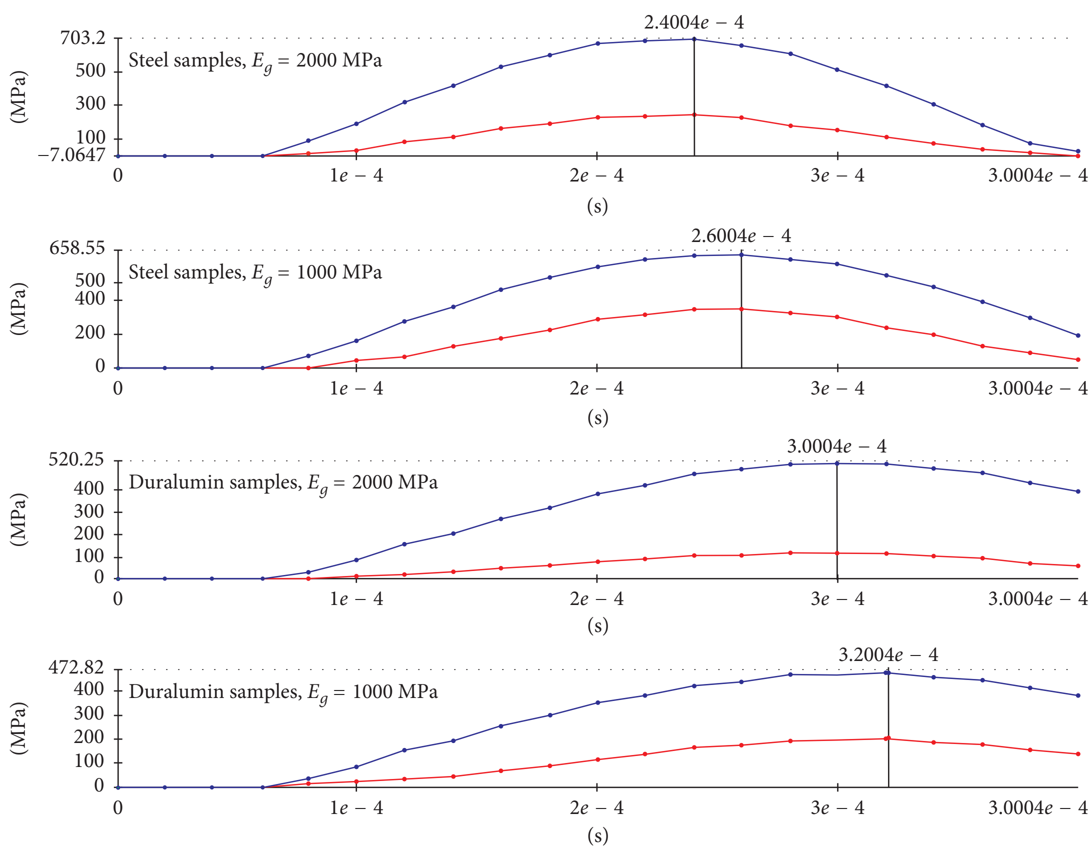

Figure 17: The time history of normal principal stresses in the joints of dynamically impact-loaded block samples in accordance with the material of the samples and Young's modulus of the adhesive (E_g).

(v) Impact strength of adhesive joints, which is determined experimentally, largely depends upon the stiffness of the research test rig.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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