STRUCTURAL ADHESIVE BEHAVIOR EXPERIMENTAL AND COMPUTATIONAL STUDY

Aiman Shibli[1]**; Mohsen A Issa, P.E., S.E., FACI, F.ASCE, M.ASCE** [2]

[1] Department of civil & Materials Engineering, University of Illinois at Chicago, Chicago, IL 60607, USA, E-mail: ashibli2@uic.edu

[2] Department of civil & Materials Engineering, University of Illinois at Chicago, Chicago, IL 60607, USA, E-mail: missa@uic.edu

Abstract: Adhesive joints are being increasingly used in structural applications due to their unique characteristics and advantages. Recently, many structural industries have considered utilizing adhesive for joining load-bearing components as an excellent candidate for replacing the traditional joining methods such bolting and riveting, especially for scenarios involving joining Fiber Reinforced Polymers (FRP) composites. The attractiveness of adhesives stems from their unique combinations of properties which include: high strength, light weight, dimensional stability, high resistance to environmental degradation and ease of use. The traditional bolted joint methods have gone a long way in creating appropriate technologies and gained years of design experience, which cannot be easily replaced. Accordingly switching from traditional joining methods to adhesives bonding in civil infrastructure applications requires a large investment to establish a level of understanding comparable to that associated with traditional joining methods. In particular, it is crucial to characterize and fully understand bonded joint behavior, strength and failure properties, and to be able to predict them for a given geometries and loads.

The objectives of this research are: i) investigate the behavior of structural adhesive by characterizing their mechanical properties, and ii) establish a representative material model that can mimic their behavior and can be used in numerical models for computational studies. Results of this work are produced by quasi-static and dynamic experiments which were performed on a structural adhesive at different loading rates. Material model has been created and validated at coupon level and system level, under quasi-static and dynamic loadings. In addition, comparison between experimental results and numerical results obtained from 3D finite element analysis showed very good correlation at different loading modes and rates.

Keywords: FRP; Reinforced Polymer; Structural Adhesive; Composites; Stiffness; Infrastructure; Civil Structure; Finite Element Analysis (FEA).

1. Introduction

Civil infrastructure applications have been increasingly using Fiber-reinforced polymer (FRP) composites due to their advantageous material properties such as their high strength, high stiffness, light weight, high resistance to environmental degradation and rapid installation. However, structural FRP components are difficult to connect using bolted joints due to the brittleness of this material. The current traditional joining methods such as bolting and riveting create stress concentrations which lead to premature failure. Many structural industries have considered utilizing adhesives for joining load-bearing components as an excellent candidate for replacing the traditional bolted joint methods, especially when dealing with fibrous materials such composites. They have been attracted to use adhesives due to several reasons: high strength, dimensional stability, and ease of use. Furthermore, using adhesive joints will lead to uniform loading without stress concentrations as compared to the bolted joints. Holes in the bolted joints are areas for stress concentrations and moisture ingress, which can impact the overall structure durability.

The traditional bolted joint methods have gone a long way in creating appropriate technologies and gained years of design experience, which cannot be easily replaced. Switching from traditional joining methods to adhesives bonding in the civil infrastructure applications requires a large investment. Currently adhesive joints for civil infrastructure applications are in its infancy due to the lack of design guidelines and consistent specifications. Although adhesive bonding have been studied and used widely in the fields of aerospace and automotive, these studies cannot be directly transferred to the civil infrastructure domain. Adhesive bonding for civil structural application have essential differences with respect to type of materials, loadings, geometries and environmental conditions.

There are several studies on structurally adhesive joints; most of these studies follow the same two assumptions. The first of which is that structural adhesives behave elastically linear. The second of which is that structural adhesives always fail cohesively. Buyukozturk et al. pointed out that more realistic assumption are needed to provide better approximations of joint strength and behavior. Reza studied the adhesive joints which are used to bond CFRP laminates to steel substrate using experimental and numerical approaches. He concluded that non-linear deformation of adhesive can contribute to redistribution of strain and joint capacity.

One of the important steps towards greater use of structural adhesives in civil structural applications is to characterize their behavior. The present study was undertaken to investigate the structural adhesive behavior and its impact on a sandwich structure behavior. Adhesive and substrates have been characterized under quasi-static and dynamic tensile loading. Elastic-plastic material models were created for the substrates (Al and PC) and different material models (elastic, elastic-plastic and elastic-viscoelastic) were considered for the adhesive in order to find out the best representative material model that can mimic the adhesive's behavior. Sandwich structures were constructed where the adhesive was sandwiched between two substrates (Al and PC). Quasi-static and dynamic bending experiments and simulations were performed on the sandwich structures, comparison between experimental results and numerical results obtained from 3D finite element analysis showed good correlation if we account the for the structural adhesive plasticity

2. Quasi-Static and Dynamic Bend Test

Sandwich structures were constructed where the adhesive was sandwiched between two substrates (Al and PC); two configurations were considered as shown in figure-1. These Sandwich structures were tested under quasi-static and dynamic loadings.

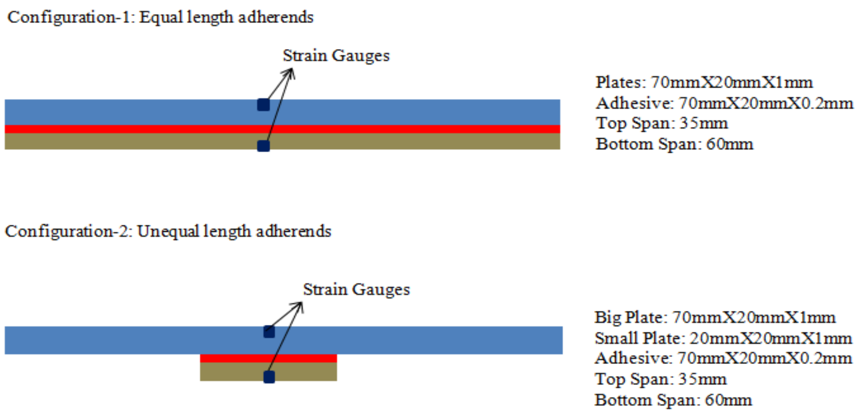

Figure 1: Two different sandwich structure configurations, equal-length plate and unequal-length plate

2.1. QUASI-STATIC BEND TEST

The planar bend test (four-point bend) has been extensively used to determine the strength of brittle materials. Similar technique was used in this study to bend the sandwiched plates in order to induce stress and strain state to the structure. The rollers from the top and bottom spans of the 4-point bend fixture were positioned 35mm and 60mm apart respectively. Two strain gauges were mounted on the sandwiched plates, one at the center of the top plate and one at the center of the bottom plate. The following are the Force-Displacement and Force-Strain test results for the two configurations:

2.1.1. *Equal-length-plate sandwich structure*

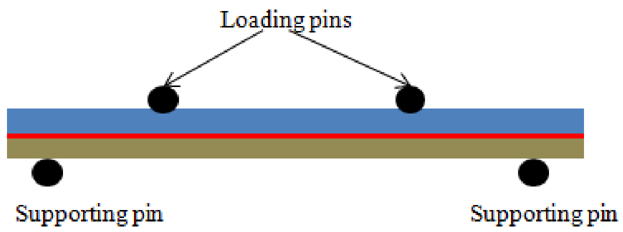

Figure 2: Equal-length-plate sandwich structure under quasi-static loading

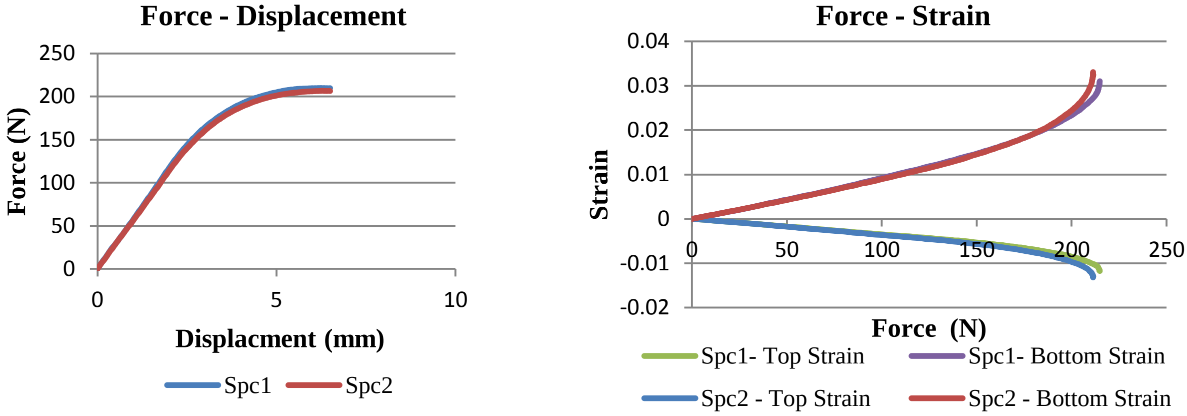

Figure 3a &3b: Force-displacement and force-strain results for the equal-length-plate sandwich structure, respectively.

2.1.2. *Unequal-length-plate sandwich structure*

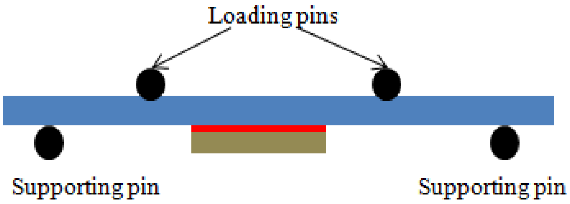

Figure 4: Unequal-length-plate sandwich structure under quasi-static loading

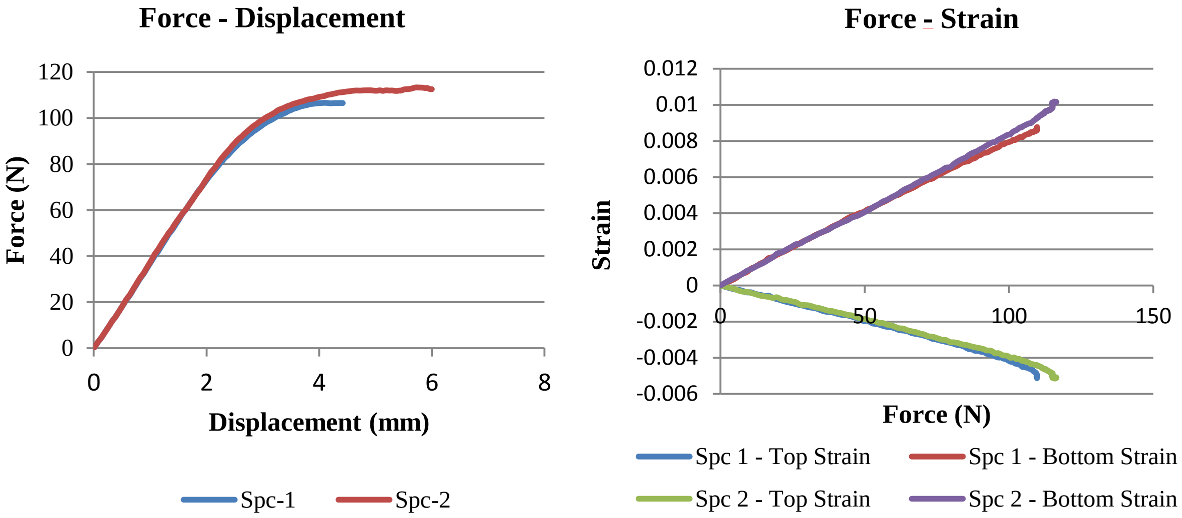

Figure 5a &5b: Force-displacement and force-strain results for the unequal-length-plate sandwich structure, respectively.

2.2. DYNAMIC BEND TEST

The test fixture used to generate dynamic planar loading of the sandwich structure was similar to that described by Reiff et al. The test vehicle was centered in the 4-point bend fixture, such that during testing the bending direction was oriented along the longitudinal axis of the sandwich structure. A steel ball was dropped on the top span in order to generate the dynamic loadings. Acceleration was monitored and used as boundary conditions in the dynamic bend simulations.

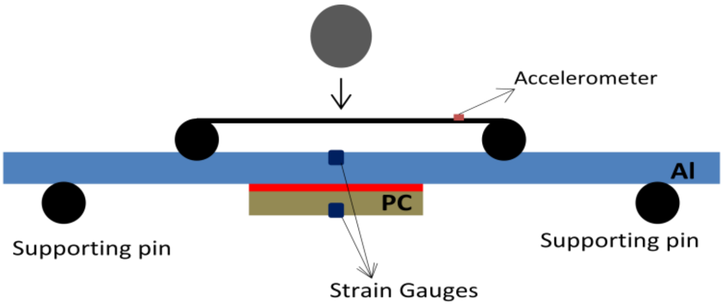

Figure 6: Unequal-length-plate sandwich structure under dynamic loading test

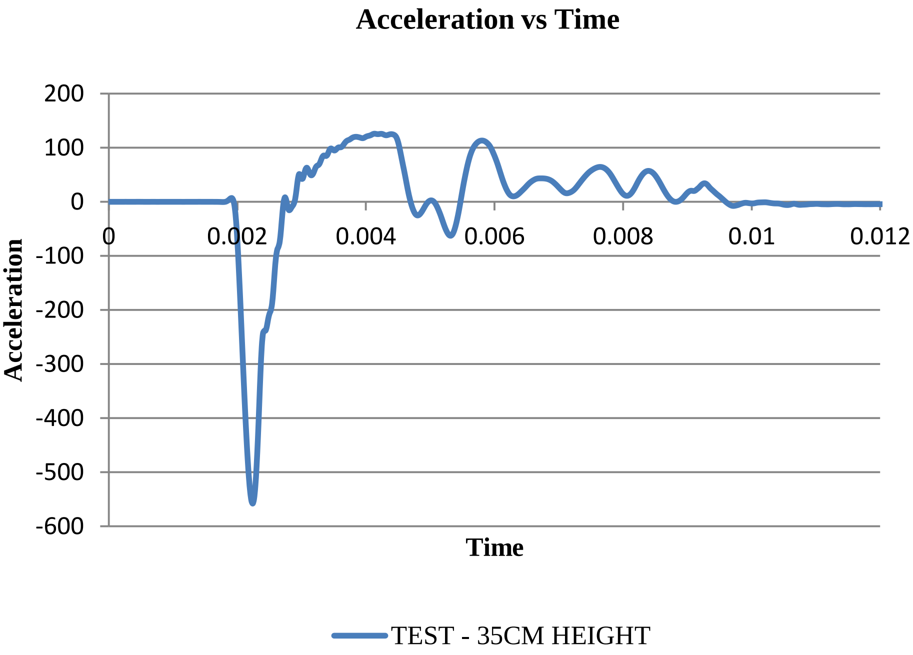

Figure 7: Acceleration test measurement of top roller during the 35cm ball drop test

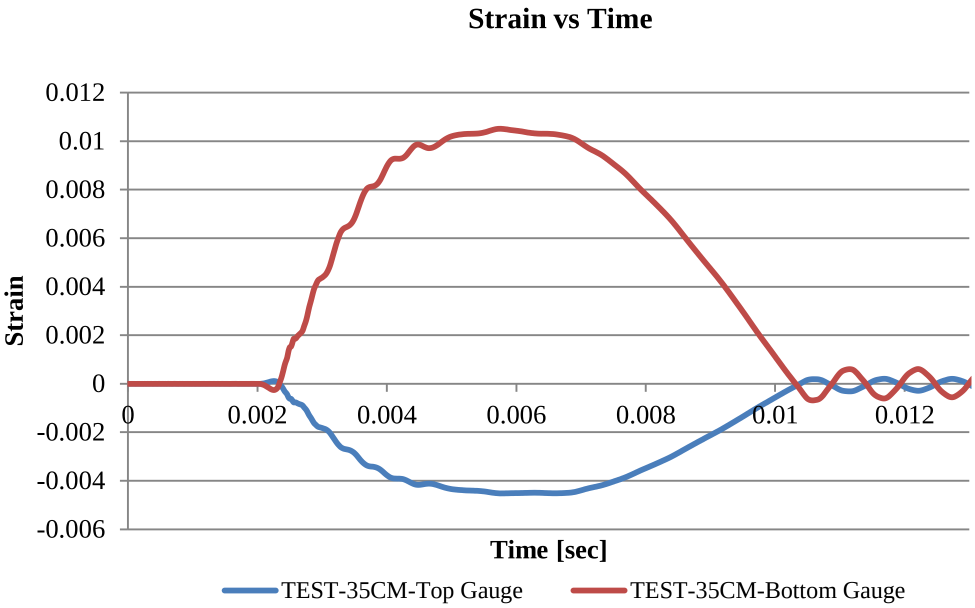

Figure 8: Strain test measurement of the top and bottom strain gauges during the dynamic test

3. Finite Element Analysis

A full three-dimensional finite element model of the sandwiched structure (Al plate, Adhesive and PC plate), and the supports of the four-point bend fixture were built using the modeling software ABAQUS. The Plates and the adhesive were modeled with reduced-integration brick elements. The two strain gauges were modeled as two membrane elements [0.8x0.8mm]. Supports of the four-point bend fixture were modeled using analytical rigid surfaces. Appropriate contact definitions were defined between the rollers and plates surfaces. The bottom support was constrained in all directions in order to prevent rigid body motion. The top support was also constrained in every direction except the vertical direction.

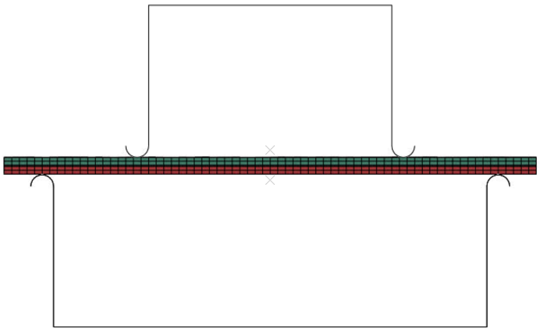

Figure 9: Plot of the simulation mesh model

3.1. QUASI-STATIC BEND SIMULATION

Two sandwich structure configurations were investigated in the quasi-static simulation as we showed earlier in figure-1 .Elastic-plastic material models were used for the substrates (Al and PC), where two different material models (elastic and elastic-plastic) were explored for the adhesive. Displacement loading was applied at a reference node of the top roller fixture. Force, displacement and strain (at the top plate center and at the bottom plate center) results were reported and correlated with experimental results to verify the best material modeling approach. The following are the results:

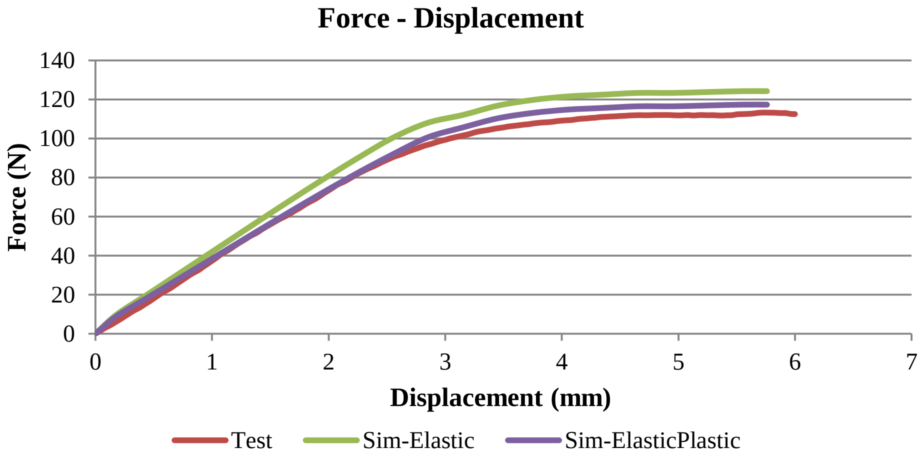

Figure 10: Force-displacement testing and simulation results of the unequal-length-plate sandwich structure

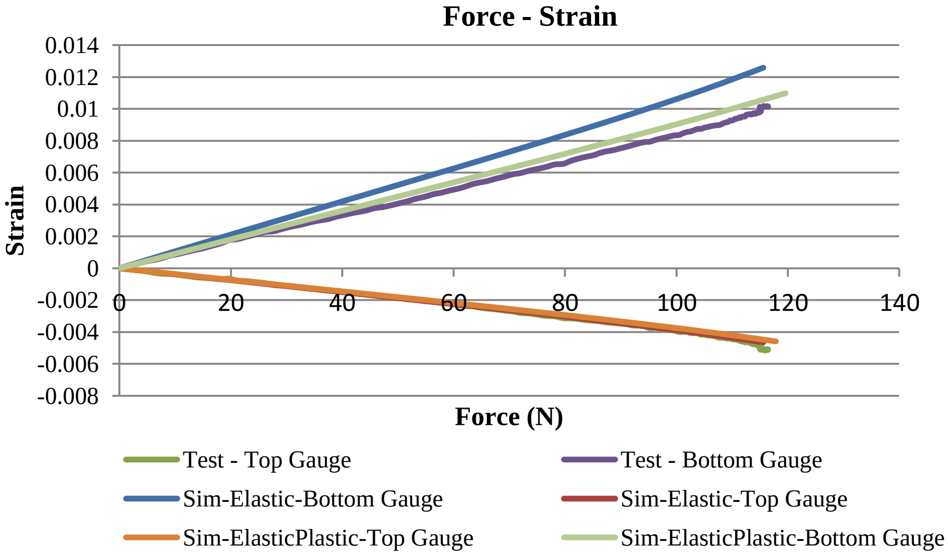

Figure 11: Force-displacement testing and simulation results of the unequal-length-plate sandwich structure

4.2. DYNAMIC BEND SIMULATION

The unequal-length-plate sandwich structure was investigated in the dynamic simulation. Elastic-plastic material models were used for the substrates (Al and PC), where three different material models (elastic, elastic-plastic and elastic-viscoelastic) were explored for the adhesive.

Reference node of the top roller fixture was controlled by acceleration data monitored and captured during testing. The methodology employed here is similar to that presented by Tee *et al* [8]. Acceleration was applied at a reference node of the top roller fixture. This modeling approach renders a very effective way to model the flexural behavior of the sandwiched structure during impact accurately and simultaneously avoids the complexity of numerical modeling of the interface material between the ball and top roller fixture. Top and bottom strain results were reported and correlated with experimental results to verify the best material model that can mimic the adhesive behavior under dynamic loading. The following are the results:

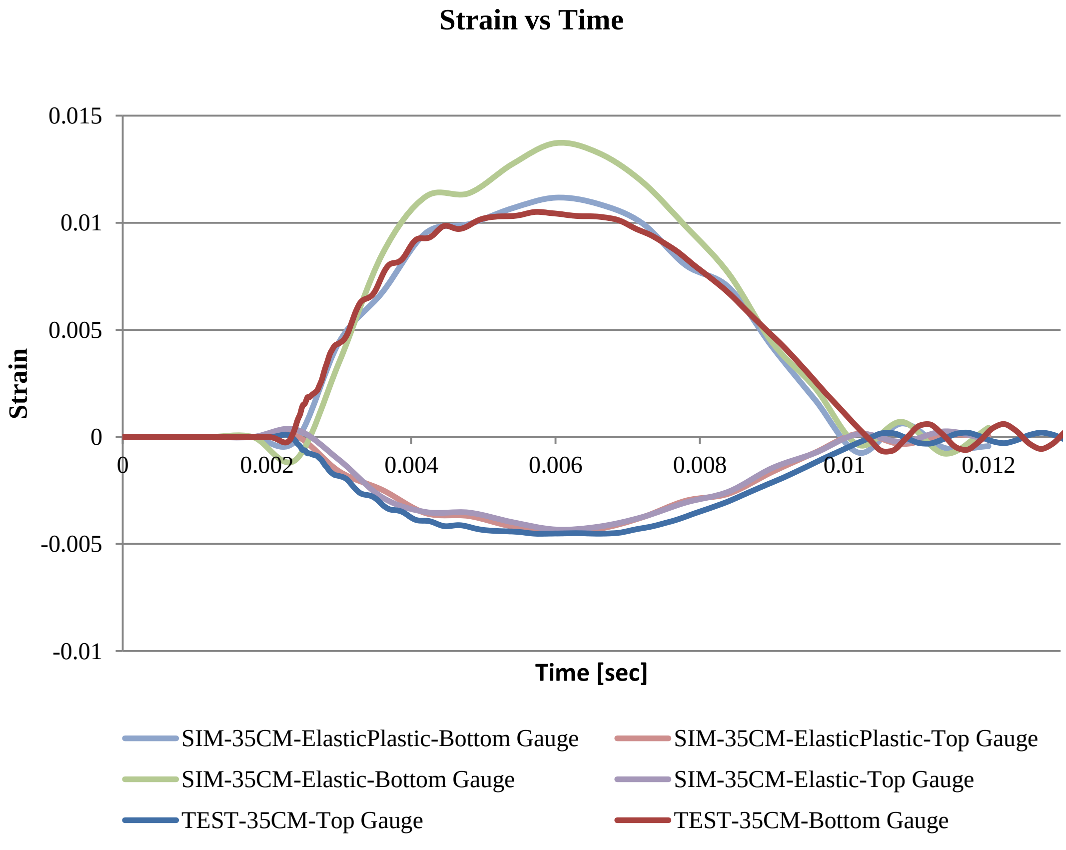

Figure 12: Strain results of the top and bottom strain gauges during dynamic testing and simulation

4. Discussion

- Quasi-Static bend simulations of the equal-length-plate sandwich structure show good correlation between experimental and simulation results, for all adhesive material models used in the simulations. Results show that force-displacement response is not affected by the adhesive stiffness which is expected as the adhesive layer will not affect the overall sandwich structure since it is much thinner and less stiff than the adherend substrates. However, for force-strain response, the results are more interesting because they are not affected by the adhesive material modeling approach. This is attributed to the fact that the bottom rollers forcing the PC plate to have the same curvature as the Al plate. The equal-length-plate configuration does not seem to serve as a good validation tool.

- Quasi-Static bend simulations of the unequal-length-plate sandwich structure show that the overall behavior of the structure is sensitive to the adhesive material modeling approach. Force-displacement results and force-strain results show that the linear-elastic material model will over predict the stiffness of the sandwich structure where the elastic-plastic material model mimics the experimental results much better. As the elastic material model does not account for plasticity, the adhesive does not soften up in simulations; and therefore, the PC plate will follow the Al plate curvature. The force-displacement results and the force-strain results show that simulation correlates well with experiments when elastic-plastic material model is used.

- Dynamic bend simulations with unequal-length-plate sandwich structure show that the overall behavior of the structure is sensitive to the adhesive material modeling approach. Strain-time simulation results at the center of top Al plate do not exhibit any dependence on the adhesive modeling approach; this is expected as the force is applied directly on the Al plate. However, strain-time simulation results at the bottom PC plate are sensitive to the adhesive material modeling approach. The elastic-plastic material modeling approach predicts the testing results very well, unlike the elastic and elastic-viscoelastic material modeling approaches which correlate poorly with experimental results because they do not account for plasticity.

5. Conclusion

A numerical and experimental study that investigates the behavior of a structural adhesive under quasi-static and dynamic loading is presented. Through the presented results which are specific to the sandwich structure materials used in this study, the following conclusions can be drawn:

- The sandwich structure with unequal-length plates is able to capture the sensitivity to the adhesive material modeling approaches. However, the sandwich structure with equal-length plates is insensitive to the adhesive layer and failed as a configuration for capturing or investigating adhesive behavior and properties.

- Comparison between numerical and experimental results from both the quasi-static and dynamic simulation results show that the elastic-plastic material model mimics the adhesive material behavior better than the elastic and elastic-viscoelastic material models, due to the ability of the elastic-plastic model to account for adhesive plasticity.
- Although both of the elastic and plastic phases of this specific adhesive are loading rate dependent, plastic behavior of the adhesive has bigger impact than its elastic behavior on the overall sandwich structure behavior. This is due to the fact that the adhesive will start deforming while the adhered substrates are still in their elastic regions.

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