Capturing structural silicone non-linear behavior via the finite element method

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Keywords

1=Structural silicone 2=Finite element analysis 3=Computer modeling

Abstract

The modeling of structural silicone presents challenges due to its non linear nature. Typical analysis methods, including rules of thumb can under or over predict actual movement and behavior depending on load. Increasing complexities of the geometry of some facades which could utilize structural silicone as a connection medium are often limited by the analysis methods available.

An investigation was carried out using advanced finite element models to correctly capture the non-linear behavior of silicone. Simulation results are compared to standardized test data.

Methods of modeling as well as an overall approach to simulating composite structures with silicone are presented.

Introduction – Modeling and façade design

The use of computer simulation technology, specifically finite element techniques, has enabled designers to derive new and innovative designs for facades. Many of these designs would not be possible without these techniques as traditional calculation methods are often limited to specific geometries and support conditions. Use of finite element techniques as a design validation tool enable custom designs to be analyzed digitally before testing or fabrication occur.

The use of finite element technology in the construction related designs is largely focused on linear models. This technique is normally sufficient for analyzing designs that under loading produce small movements and use materials in their linear response zone. Several types of non-linear simulations have become more prevalent, mostly focusing on the impact of non-linear geometry response. The incorporation of non-linear material response is often neglected as for most materials this type of response is outside of the working zone.

The exception to this is silicone, which is inherently non-linear and difficult to model. As a material structural silicone is highly versatile and is an enabler to many advanced designs. Many of the design guides, such as ASTM C 1401, produced by industry standards groups as well as manufacturers rely on simplified calculations to estimate required sizes. [1] This is due to the complexities of the materials' behavior. In addition, there is a general absence of guidance as to how to estimate the movement of structural silicone under loading.

Combined, these inhibit the simulation of structural silicone in finite element models as very little guidance exists on reasonable parameters that could be used to capture its behavior accurately. As a result modeling is difficult to validate. To add to this most commercial analysis packages do not readily provide a suitable model with parameters relatable to published data. The end result is a general limitation as to what can be modeled.

In trying to determine the behavior of glass structures via simulation this can limit the reliability of the simulations. Often these designs rely on structural silicone to pass loads from one key element to the next. Capturing the stability of the system as a whole and predicting its' buckling behavior is often made more difficult by the inability to properly model the silicone in the system In this respect, having a better material model would be highly beneficial as it would allow for a more accurate prediction of the structure behavior as a whole system.

Objective

The objective of this study was to develop a general purpose method of capturing the behavior of structural silicone in a finite element simulation. Ideally this could be done based on standardized test results or data. The larger goal that could result from this is the ability to capture fully composite behavior in a digital simulation. This could further the development of innovative designs in the arena of building facades, and other glass structures where structural silicone is used as a key element in the design.

Methods

The study focused on calibrating a finite element model's force versus displacement behavior to that of a laboratory test. To simplify acquisition of test data to compare simulations to, a standardized test methodology was chosen as a basis. The test method, ASTM C 1135, is designed as a tensile method of determining sealants adhesion properties to a specific substrate.[2] The method calls for a specific geometry of both the sealant as well as the substrates [Figure 1]. For the silicones used in this study, the samples were known to adhere well to their substrates, no adhesive failure was reported. Material test data was provided for tensile, shear and compressive loading by several manufacturers.

Figure 1

Test sample geometry as defined by ASTM C 1135.

Modeling results were produced using LS-DYNA, a commercially published, non-linear, finite element package. LS-DYNA was designed to capture transient and highly non-linear behavior. Typical applications include metal forming processes, earthquake simulations on building structures as well as automobile crashes. One advantage of the package is that it has a large and diverse material library, including about one dozen models that are applicable for capturing rubber behavior.

Many material models used in finite element analysis are calibrated to material data that can be related to a uniaxial test. This is generally sufficient to capture their behavior in the typical loading range that the materials will be exposed to. Silicone as a material is largely incompressible, and when compared to a traditional structural material is of low stiffness. This complicates capturing accurate uniaxial test data. Investigations towards this approach were not successful in matching real behavior.

The material model used in this study was a continuum rubber model derived from a study by Blatz and Ko.[3] It is a one parameter model that relies on a shear modulus to capture behavior. The model uses a fixed Poisson's ratio of 0.463 to capture the incompressible nature of silicone. The shear modulus used in the simulations was determined by a curve fitting the model results to that of the tensile data. Simulations were then carried out under compressive and shear loadings to replicate test data [Table 1]. For comparative purposes simulations were also carried out using a standard linear material model with the same parameters specified in Table 1.

For comparative purposes simulations were also performed substituting a linear material model with an equivalent Young's modulus. A view of the modeled states can be seen in Figure 2.1 through 2.4.

Results

Simulation results for tension loading using the continuum rubber material model [Figure 3] were within 20% of that of the test data for the range of strain varying to 100%. Between the strain range of 25% and 100% this differential drops by approximately half. The bulk of the error of the model when compared to average test data occurred at low strain values. For this movement range, the models over predicted silicone elongation in comparison to the test data. It should be noted that as displayed in Figure 3, the test data which is based on a small sample size had some variation. This was especially noticeable for Silicone C, which had an average data point differential of 8% from that of the average over the strain range investigated.

Simulations in compressions using the continuum rubber model as presented in Figure 4, provided similar accuracy to that of the tensile simulations. Maximum error for silicone A and B were 14% and 23% respectively. For both samples, the models generally under predicted the compression of the silicone at moderate loadings. Interestingly, the difference of the model response from that of test points for both samples was maximum between 20% and 25% strain.

Figure 5 shows the results of simulations for the continuum rubber model under shear loading. The simulations under shear loading for silicone A produced behavior that was within 12% of the test data over the range of strains examined. Silicone B maintained an offset of 13% to 23% over the range investigated.

Sensitivity studies were carried out to determine if the model was defendant on mesh sizing as well. The mesh for the studies described utilized a mesh size of approximately 3 mm. In relation to the geometry used in the simulations this results in the silicone cross section

Material	Manufacturer specified movement capacity	Effective shear modulus used in simulations	Equivalent Young's modulus with ν=0.463	Test data available
Silicone A	10%	0.60 MPa	1.75 MPa	Tension, compression, shear
Silicone B	50%	0.34 MPa	1.00 MPa	Tension, compression, shear
Silicone C	25%	0.51 MPa	1.50 MPa	Tension

Table 1

Structural silicone test data used in calibrating the modeling study.

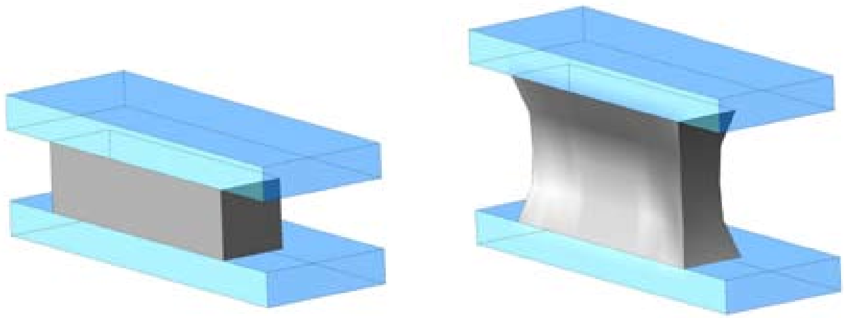


Figure 2.1 and 2.2

Base model geometry prior to loading, and simulated deflection under tensile loading.

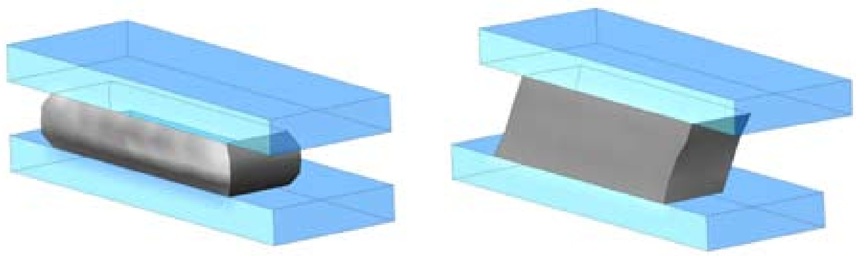


Figure 2.3 and 2.4

Modeled compression and shear loading.

Figure 3

Tensile simulation results using the continuum rubber model compared to test data. Test data points are representative of the average measurement. Bars on test data points represent minimum and maximum recorded point.

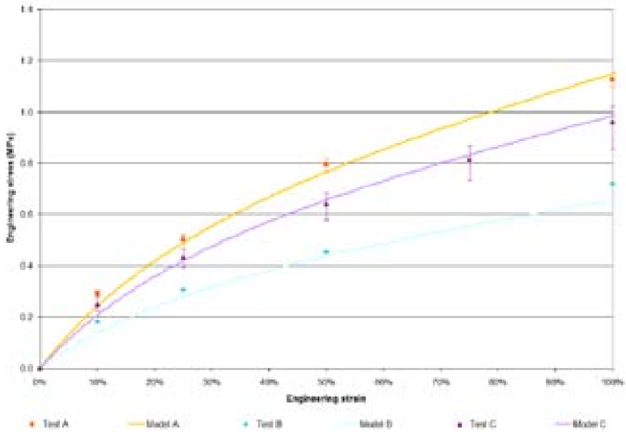
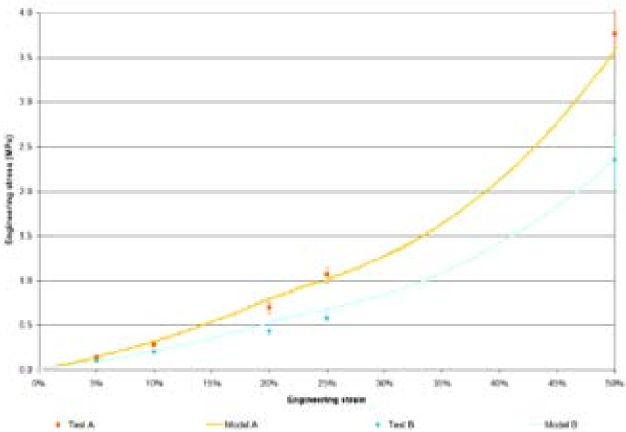


Figure 4

Compression simulation results using the continuum rubber model compared to test data. Test data points are representative of the average measurement. Bars on test data points represent minimum and maximum recorded point.



containing four elements between the simulated substrates [Figure 6.1]. To test mesh dependency the mesh was refined to half the nodal spacing of the base mesh used [Figure 6.2]. Results of tensile simulations showed an average difference form the base mesh of less than 0.5%. Simulations of coarser meshes were also tested but did not return results that were close to that of the base mesh.

For comparative purposes, simulations were carried out for each of the silicones under tension, compression and shear using a linear material model. The results of these simulations as shown in Figure 7 through 9 showed some correlation to the test data profile, but in a more limited range than that of the continuum rubber model. As shown in Figure 7, simulations in tension are comparable in error to that of the continuum rubber model up to strains of 50%. Beyond this strain significant deviations are encountered. Under compression loading [Figure 8] deviations from the continuum rubber model are encountered at approximately 30% strain. The response under shear loading [Figure 9] produced comparable results to that of the continuum rubber model.

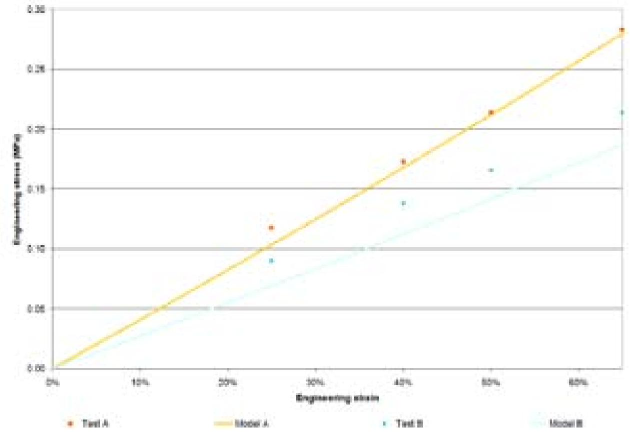
It should be noted that when using the linear material model the simulations became unstable at high strains. Several of the simulations diverged and stopped at strains where the continuum rubber model is still usable.

Conclusions

The results of the studies discussed show that structural silicone can be modeled with some accuracy using a single parameter continuum rubber model. These simulations also show relatively consistent behavior under different loading conditions. In comparison, simulations utilizing a linear material model can produce results albeit in a more limited range of loading.

Figure 5

Shear simulation results using the continuum rubber model compared to manufacturer test data. Note that for shear tests only the averaged results were available.



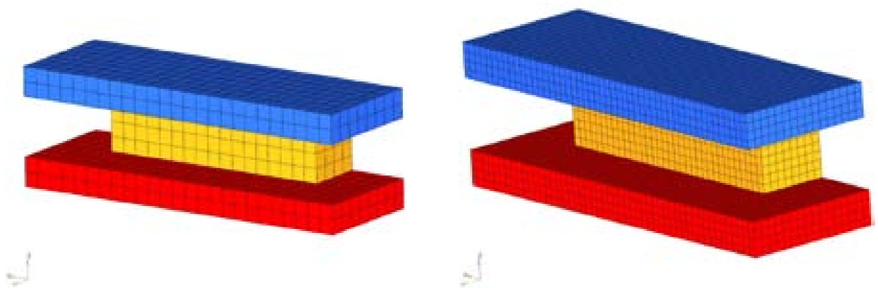
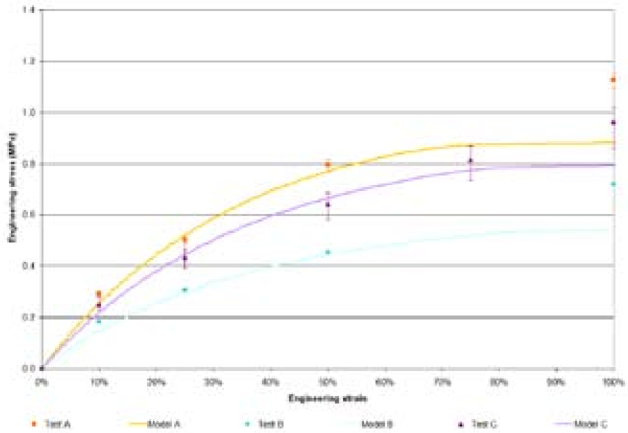


Figure 6.1 and 6.2

Base mesh with a nodal spacing of approximately 3mm compared to the refined mesh which used a spacing of half. The refined mesh model utilizes eight times the number of element of that of the base.

Figure 7

Tensile simulation results using a linear material model compared to test data. Test data points are representative of the average measurement. Bars on test data points represent minimum and maximum recorded point.



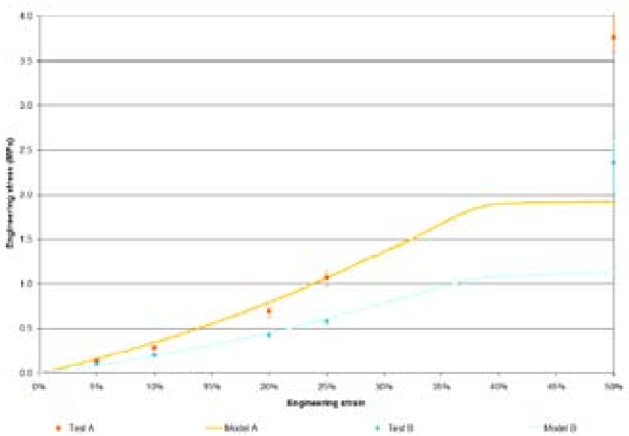


Figure 8

Compression simulation results using a lineal material model compared to test data. Test data points are representative of the average measurement. Bars on test data points represent minimum and maximum recorded point.

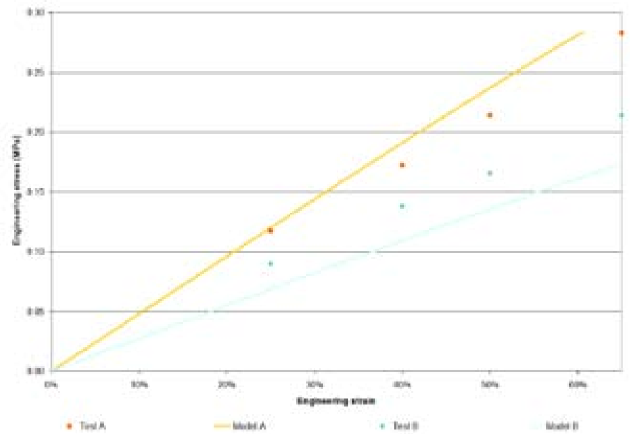


Figure 9

Shear simulation results using a lineal material model compared to test data. Test data points are representative of the average measurement. Bars on test data points represent minimum and maximum recorded point.

The study presented here analyzes specific loading conditions that are unlikely to occur in isolation in practice. While test data for combined loading was not available for this study, it would be reasonable to assume that combined loading cases would responses of similar accuracy. Future work could demonstrate this.

The study also highlights some potential problems with capturing silicone behavior in a finite element simulation. The designs using structural silicone for the built environment typically revolve around small strain behavior, under 20%. In this study this regime specifically showed the largest deviation from test results. In some cases this may be acceptable as simulations can produce conservative results in that silicone movement is overestimated at a given loading. In cases where a more exact response is required, further calibration of the model's parameters may be required.

For the purposes of modeling combined behavior of elements joined by structural silicone, i.e. a unitized curtain wall panel, the deviations of the model from test measurements may be inconsequential. For these cases the error in simulated silicone displacement within 20% of the silicone strain, may not be meaningful in the larger system behavior.

There may also be cases where a linear material model may be used in lieu of the continuum rubber model studied here. Within the range of small strains, this model seems suitable. However, the response of the model at higher strains is unrealistic. In simulations where the expected response is unknown this can become problematic, especially under combined loading as it may not be clear if the model is producing reasonable results. It should be noted that in all cases a non-linear geometry solver should be used to capture the response of silicone.

Obtaining base material data for either the linear or continuum rubber model is not simple. Most silicone manufacturers do not report an effective Young's or shear modulus. This is not surprising as the values are not determined as easily as they are for more typical engineering materials. The suggested design strength values for structural silicone as published in standards such as ASTM C 1401 also do not provide a good correlation to the manufacturers published movement capacity.[1] This can be clearly seen in the results of the simulations, where the manufacturer's movement capacity does not occur at the typical recommended design stress of 0.14 MPa. It is therefore recommended that extended test data be acquired from the manufacturer as was done for this work.

Finally, in this study the test data that was used was of small sample size. Additionally, noticeable variations between subsamples of the same data point were found. Further studies should address this through the use of a larger sample size which can be statistically correlated to a more accurate degree.

Summary

The simulations show that modeling structural silicone can be carried out with reasonable results using a one parameter model. The study also demonstrates that modeled behavior is consistent under various loading mechanisms. The methodology and results of the study can be used towards future work in trying to capture larger scale composite behavior in cladding systems and glass structures.

Acknowledgements
We would like to acknowledge the manufacturers who provided the test data that was used in the development of this work.

References

[1] ASTM C 1401: Standard Guide for Structural Sealant Glazing, ASTM International, 2007.
[2] ASTM C 1135: Standard Test Method for Determining Tensile Adhesion Properties of Structural Sealants, ASTM International, 2005.
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