

Article

Simulation and Experiment on the Performance Evolution of Silicone Sealant for Hidden Frame Glass Curtain Wall

Chuang Li ^{1,*}, Guanyu Chen ², Yu Wang ^{2,*}, Zijie Xu ², Jiahui Ji ¹ and Shunzhe Yang ¹

¹ School of Transportation and Geomatics Engineering, Shenyang Jianzhu University, Shenyang 110168, China; 13555878323@163.com (J.J.); m15042542936@163.com (S.Y.)

² School of Civil Engineering, Shenyang Jianzhu University, Shenyang 110168, China; 15940268049@163.com (G.C.); tiger19990111@126.com (Z.X.)

* Correspondence: leechuang1990@sjzu.edu.cn (C.L.); wangyu1977@sjzu.edu.cn (Y.W.)

Abstract

Silicone structural sealant is a key material in glass curtain wall systems, for which an appropriate hyperelastic constitutive model is essential for enhancing the accuracy of finite element analysis (FEA). Firstly, an improved comprehensive fixture of silicone structural sealants for tensile and shear tests was conducted. Secondly, the hyperelastic constitutive model was selected to fit data through experiments, which was comprehensively evaluated using three indicators, such as goodness of fit, root mean square error, and relative deviation. Thirdly, this constitutive model was utilized for FEA validation under uniaxial tensile and shear conditions, the Mooney–Rivlin 3 (M-R3) model demonstrated optimal fitting performance. Finally, the mechanical response of the glass curtain wall under wind load was systematically analyzed under various debonding scenarios. This study reveals the failure evolution law of silicone structural sealant under actual service conditions, providing practical guidance for enhancing the safety design of glass curtain wall structures.

Keywords: silicone structural sealant; uniaxial tension; hyperelastic constitutive model

1. Introduction

Silicone structural sealant is not merely a colloidal material but rather a crosslinked elastomeric network based on polydimethylsiloxane (PDMS), often reinforced with fumed silica fillers and containing crosslinkers and catalysts [1]. Owing to its superior compatibility and long-term stability, this material has been extensively applied to structural sealing of curtain walls. As critical determinants in curtain wall engineering, the mechanical properties of silicone structural sealants (e.g., tensile strength, elongation at break, and modulus) govern load-transfer efficiency between components, ensuring structural synergy under combined wind-induced dynamic stresses (up to 500 Pa) [2,3].

Extensive research on the mechanical properties and constitutive models of silicone structural sealants has attracted the attention of scholars. Guo et al. [4] discovered that the mechanical behavior of silicone structural sealant exhibits significant hyperelastic characteristics under monotonic loading conditions, providing a basis for hyperelastic constitutive modeling. Zhou et al. [5] proposed the shear properties of silicone sealant with different stress angles and found that the modulus increases with the stress angle, suggesting the need for angle-dependent constitutive descriptions. Shi et al. [6] conducted tests on

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the shear performance of three types of structural sealant joints and concluded that silicone structural sealant had a lower shear strength but stronger deformation ability. Hagl et al. [7] suggested that the failure of silicone structural sealant bonding nodes is primarily governed by material, which precedes bondline failure in practical engineering applications. Staudt et al. [8] investigated the failure behavior of silicone adhesive in bonded connections and proposed a strain-based failure assessment for cohesive adhesive failure, which was valid for bonded connections in the form of linear beads for cohesive failure of the adhesive. Jobst et al. [9] addressed the material and lifetime modeling of silicone adhesive; an elastomeric silicone adhesive was characterized with different thermomechanical methods. Guo et al. [10] conducted a series of multiscale experiments, including uniaxial tension, uniaxial compression, simple shear, and scanning electron microscopy (SEM) observation to characterize the mechanical behaviors and microstructure features of silicone adhesive. Marckmann et al. [11] compared twenty hyperelastic models for rubber-like materials, including stretch-range validity, to reproduce different types of loading conditions. Boyce et al. [12] reviewed constitutive models of rubber elasticity, analyzed several recent and classic statistical mechanics and continuum mechanics models of incompressible rubber elasticity.

Collectively, these studies contribute to the development of constitutive models for silicone structural sealants, covering hyperelasticity, stress-angle dependence, large deformation behavior, and the Mullins effect. Silicone structural adhesives exhibit complex mechanical behaviors in glass curtain wall structural applications, and accurately distinguishing these behaviors is a prerequisite for establishing reliable constitutive models. Under monotonic loading conditions, silicone adhesives display typical hyperelastic behavior, with their stress–strain relationship describable by a strain energy density function [13]. However, in engineering service environments, silicone adhesives involve more complex responses. Under cyclic loading, the Mullins effect occurs, manifesting as a permanent reduction in stiffness after the first loading cycle. Under sustained loading or alternating temperature conditions, viscoelastic behavior emerges, including stress relaxation and creep. The coupling effects among the aforementioned behaviors make the constitutive modeling of silicone adhesives extremely challenging [11,12].

Among these aspects, hyperelasticity provides the most fundamental and computationally efficient description, and its constitutive model is usually the best option for FEA of the mechanical properties of simple rubber compounds. The mathematical foundation of these hyperelastic models traces back to the early work of Mooney [13], who first proposed a strain energy function for hyperelastic deformations of isotropic incompressible elastomers, which was subsequently extended by Rivlin [14] and Ogden [15]. Luo et al. [16] fitted three hyperelastic constitutive models based on the uniaxial tensile test data of XM23 adhesive. Wang et al. [17] applied five hyperelastic constitutive models to fit the test data of fluorosilicone rubber, and evaluated the models based on two regression analysis indicators, namely the root mean square error. Hu et al. [18] carried out three basic mechanical tests on carbon black-filled rubber to explore the fit quality of various hyperelastic constitutive models. Furthermore, studies [19] employed distinct hyperelastic constitutive models to characterize experimental datasets, followed by systematic evaluation of their respective fitting results. Conventional hyperelastic models fail to adequately account for the shear mechanical properties of the material, making it difficult to effectively simulate the constitutive behavior of silicone sealants [20].

The purpose of this study is to propose a new constitutive model that effectively captures the shear mechanical behavior of silicone sealants under wind loads to address the limitation of conventional hyperelastic models. In this paper, we design a test fixture that can simultaneously perform tensile and shear tests on silicone structural sealants, propose a constitutive model for silicone structural sealants considering the shear effects together

with an optimization method, analyze the mechanical response of glass curtain walls under wind loads in different debonding scenarios, and reveal the influence of debonding defects on the structural safety of curtain walls, while providing theoretical support for engineering design and maintenance.

2. Basic Theory of Hyperelasticity in Rubber Materials

The phenomenological hyperelastic model is based on experiments and mechanics. It describes the mechanical response of materials through a strain energy function, featuring a concise formulation and high computational efficiency, and is therefore widely used in engineering. Typical examples include the Neo–Hookean model, the Mooney–Rivlin model, the Ogden model, and the Yeoh model.

2.1. Strain Energy Density Function

Mooney et al. [21] proposed a phenomenological theory of strain energy density, which was applicable to incompressible elastomers undergoing large deformation. The material was assumed to be isotropic and capable of large elastic deformation, irrespective of volume changes. Regarding deformation tensor invariants (I_1 , I_2 , I_3) as independent variables, the strain energy density function of rubber material was as follows [22].

$$W = f(I_1, I_2, I_3) \quad (1)$$

$$I_1 = \text{tr}(\mathbf{B}) = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \quad (2)$$

$$I_2 = \frac{1}{2} \{ [\text{tr}(\mathbf{B})]^2 - \text{tr}(\mathbf{B})^2 \} = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_1^2 \lambda_3^2 \quad (3)$$

$$I_3 = \det(\mathbf{B}) = \lambda_1^2 \lambda_2^2 \lambda_3^2 \quad (4)$$

$$\mathbf{F} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \quad (5)$$

where $\mathbf{B} = \mathbf{F}\mathbf{F}^T$ is the left Cauchy Green deformation tensor, λ_i ($i = 1, 2, 3$) is the principal stretch ratio of the rubber material, $\lambda_i = 1 + \varepsilon_i$, and ε_i is the principal strain along the axis direction. For incompressible materials, Equation (1) is expressed as follows:

$$W = \sum_{i+j=1}^N c_{ij} (I_1 - 3)^i (I_2 - 3)^j \quad (6)$$

For uniaxial tensile testing, the principal stretch ratio (λ_i) of each direction has the following relationship:

$$\lambda_1^{-1/2} = \lambda_2 = \lambda_3 \quad (7)$$

I_1 and I_2 are defined as follows:

$$\begin{aligned} I_1 &= \lambda^2 + 2\lambda^{-1} \\ I_2 &= 2\lambda + \lambda^{-2} \end{aligned} \quad (8)$$

The principal stress is as follows:

$$\sigma = 2 \left((1 + \varepsilon) - \frac{1}{(1 + \varepsilon)^2} \right) \left(\frac{\partial W}{\partial I_1} + \frac{1}{1 + \varepsilon} \frac{\partial W}{\partial I_2} \right) \quad (9)$$

For the shear experiment, the principal stretch ratio (λ_i) of each direction has the following relationship:

$$\lambda_3 = \lambda_1^{-1}, \quad \lambda_2 = 1 \quad (10)$$

The equations of I_1 and I_2 are as follows:

$$I_1 = I_2 = \lambda^2 + \lambda^{-2} + 1 \quad (11)$$

The principal stress is as follows:

$$\sigma = 2 \left((1 + \varepsilon) - \frac{1}{(1 + \varepsilon)^3} \right) \left(\frac{\partial W}{\partial I_1} + \frac{\partial W}{\partial I_2} \right) \quad (12)$$

2.2. Neo-Hookean Model

The Neo-Hookean model [13] is an unconditionally stable model that is applicable to rubber products with a small strain range, and its strain energy density function equation is as follows:

$$W = \frac{1}{2} \mu (I_1 - 3) \quad (13)$$

where μ is the shear modulus. By substituting (13) into Equations (9) and (12), the relationship between nominal principal stress and strain can be obtained. Under uniaxial tension, the equation of principal stress is as follows:

$$\sigma = \mu \left[(1 + \varepsilon) - (1 + \varepsilon)^{-2} \right] \quad (14)$$

Under the action of shear force, the equation for principal stress is as follows:

$$\sigma = \mu \left[(1 + \varepsilon) - (1 + \varepsilon)^{-3} \right] \quad (15)$$

2.3. Mooney-Rivlin Model

The strain energy equation of the Mooney-Rivlin [14,15] model is suitable for moderate strain ranges ($\leq 200\%$) and can be represented by I_1 and I_2 .

$$W = \sum_{i,j=0}^{\infty} c_{ij} (I_1 - 3)^i (I_2 - 3)^j \quad (16)$$

where C_{ij} is the parameter of the material constitutive model, which is obtained by fitting experimental data. By substituting Equation (1) into Equations (9) and (12), the principal stresses under uniaxial tension are as follows:

$$\sigma_2 = 2C_{10} \left[(1 + \varepsilon) - (1 + \varepsilon)^{-2} \right] + 2C_{01} \left[1 - (1 + \varepsilon)^{-3} \right] \quad (17)$$

$$\sigma_3 = 2 \left\{ \left[(1 + \varepsilon) - \frac{1}{(1 + \varepsilon)^2} \right] (C_{10} + C_{11} (2(1 + \varepsilon) + (1 + \varepsilon)^{-2} - 3)) + \left[(1 + \varepsilon)^{-1} (C_{01} + C_{11} [(1 + \varepsilon)^2 + 2(1 + \varepsilon)^{-1} - 3]) \right] \right\} \quad (18)$$

The principal stresses under the action of shear force are as follows:

$$\sigma_2 = 2(C_{10} + C_{01}) \left[(1 + \varepsilon) - (1 + \varepsilon)^{-3} \right] \quad (19)$$

$$\sigma_3 = 2 \left((1 + \varepsilon) - \frac{1}{(1 + \varepsilon)^5} \right) \left(C_{10} + C_{01} (1 + \varepsilon)^2 + C_{11} ((1 + \varepsilon)^6 + (1 + \varepsilon)^{-4} - 1 - (1 + \varepsilon)^2) \right) \quad (20)$$

2.4. Ogden Model

The Ogden hyperelastic constitutive model [23] is suitable for large strain ranges (>200%) and multiaxial complex loading scenarios, with its strain energy density function expressed in terms of three principal stretch ratios ($\lambda_1, \lambda_2, \lambda_3$).

$$W = \sum_{i=1}^n \frac{\mu_i}{\alpha_i} (\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) \quad (21)$$

where μ_i and α_i are both material parameters, and n is the order. By substituting Equation (21) into Equations (9) and (12), the principal stress under uniaxial tension is as follows:

$$\sigma = \sum_{i=1}^N \mu_i \left[(1 + \varepsilon)^{\alpha_i - 1} - (1 + \varepsilon)^{-\frac{1}{2}\alpha_i - 1} \right] \quad (22)$$

The principal stress under the action of shear force is as follows:

$$\sigma = \sum_{i=1}^N \mu_i \left[(1 + \varepsilon)^{\alpha_i - 1} - (1 + \varepsilon)^{-\alpha_i - 1} \right] \quad (23)$$

2.5. Yeoh Model

The Yeoh model [24] is a classical constitutive model used for describing the mechanical behavior of rubber-like hyperelastic materials. It takes the first strain invariant (I_1) as the variable and is notably characterized by its ability to effectively capture the stress-strain behavior over a large deformation range (up to 300% or higher). The strain energy density function is as follows:

$$W = \sum_{i=1}^n C_{i0} (I_1 - 3)^i \quad (24)$$

where n is the order. The parameters of the material constitutive model can be obtained by fitting experimental data. By substituting Equation (24) into Equations (9) and (12), the principal stress under uniaxial tension is as follows:

$$\sigma = \sum_{i=1}^3 2iC_{i0} \left[(1 + \varepsilon) - (1 + \varepsilon)^{-2} \right] \left[(1 + \varepsilon)^2 + 2(1 + \varepsilon)^{-1} - 3 \right]^{i-1} \quad (25)$$

where ε is the strain. The principal stress under the action of shear force is as follows:

$$\sigma = \sum_{i=1}^3 2iC_{i0} \left[(1 + \varepsilon) - (1 + \varepsilon)^{-3} \right] \left[(1 + \varepsilon)^2 + (1 + \varepsilon)^{-2} - 2 \right]^{i-1} \quad (26)$$

3. Tensile and Shear Tests

3.1. Tests

The silicone sealant used in this study is SS622, manufactured by Guangzhou Baiyun Chemical Industry Co., Ltd (Guangzhou, Guangdong, China). The sealant is a two-part structural silicone sealant whose curing reaction follows an alcohol-condensation (dealcoholization) mechanism. The product indicators are listed in Table 1. After mixing with the curing agent, the silicone sealant is injected into a mold to form dumbbell-shaped specimens. The specimens are cured in the mold and conditioned under standard conditions (temperature 23 ± 2 °C, relative humidity $50 \pm 5\%$) for 7 days. After demolding, the specimens are inspected for surface defects (bubbles or material shortages) prior to tensile

testing. The substrates are then cleaned with acetone in accordance with standard procedures.

Table 1. Silicone structural sealant product parameters.

Parameters	Indicator Range	Sample Indicators
Bonding strength/MPa	≥ 0.6	1.57
Hardness/Shore A	20~60	46

We evaluate the mechanical performance of the sealants via uniaxial tensile and shear tests using an electronic universal testing machine (WDW-20 type, Shandong Wanchen Testing Machine Co., Ltd., Jinan, China). The tests are carried out in compliance with Chinese standards JG/T 475-2015 [25], GB/T 16776-2005 [26], and HG/T 3869-2008 [27], with product parameters given in Table 1. Among these, the clamping fixtures used are shown in Figure 1a; the maximum testing force was 2 kN, and the testing force measurement range was from 0.5% to 100% F.S. The uniaxial tensile test specimens were made into dumbbell-shaped specimens with effective lengths, widths, and thicknesses of 33 mm, 6 mm, and 3 mm, respectively, according to the standard (GB/T528-2009) [28], as shown in Figure 1b. The shear test specimens (shaded area) were made into rectangular rubber strips with lengths, widths, and thicknesses of 50 mm, 12 mm, and 12 mm, respectively, according to the standards (JG/T475-2015) [25] and (HG/T 3869-2008) [27]. Then, the bonding substrates were selected as transparent uncoated float glass and anodized aluminum plate. The modified silicone sealant test fixture was employed for the test. Finally, the experiments were conducted under standard test conditions with a tensile rate of 10 mm/min, as shown in Figure 2. The stress–strain curve is shown in Figure 3.

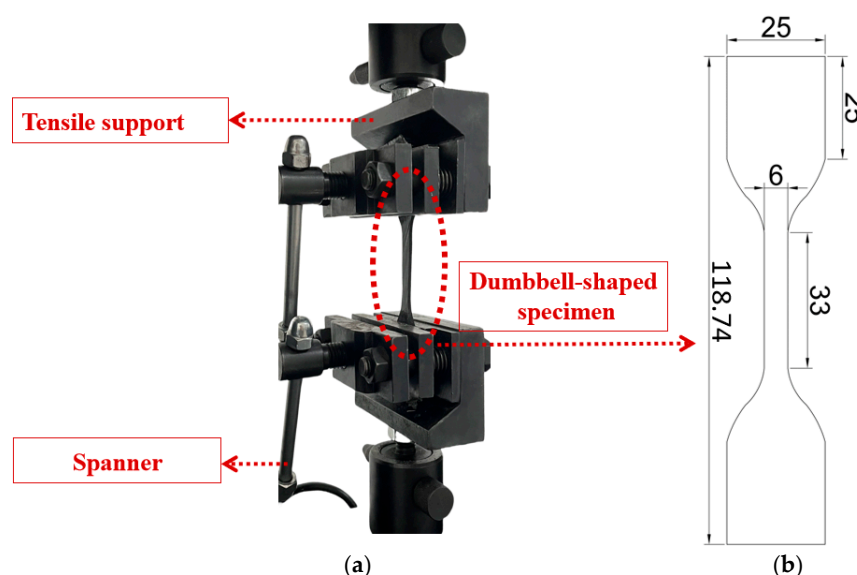


Figure 1. Uniaxial tensile test profile: (a) clamping fixtures and (b) dumbbell sample size.

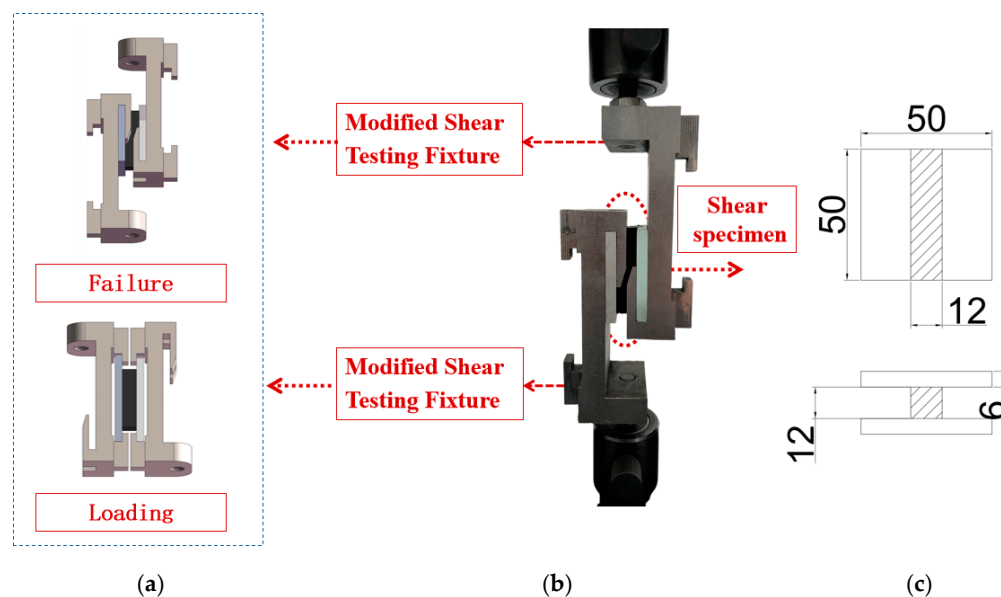


Figure 2. Shear test profile: (a) modified shear testing fixture, (b) clamping fixtures, and (c) shear sample size.

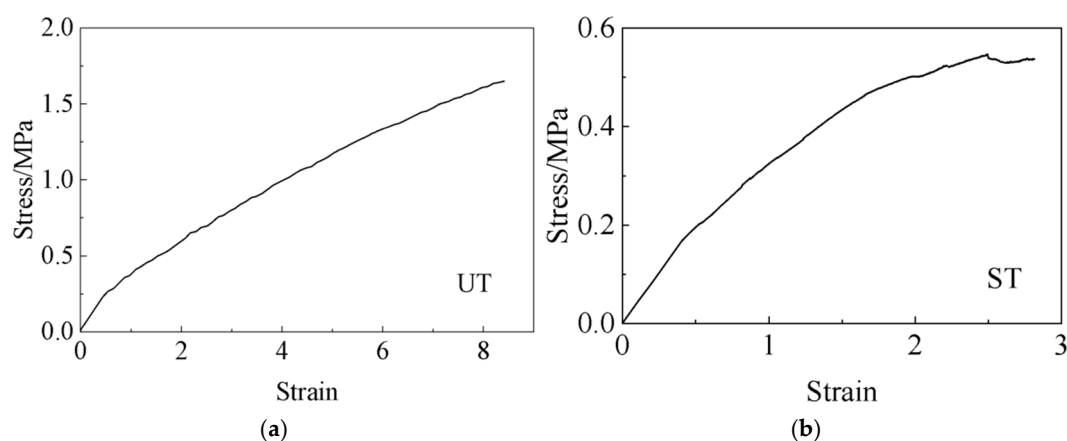
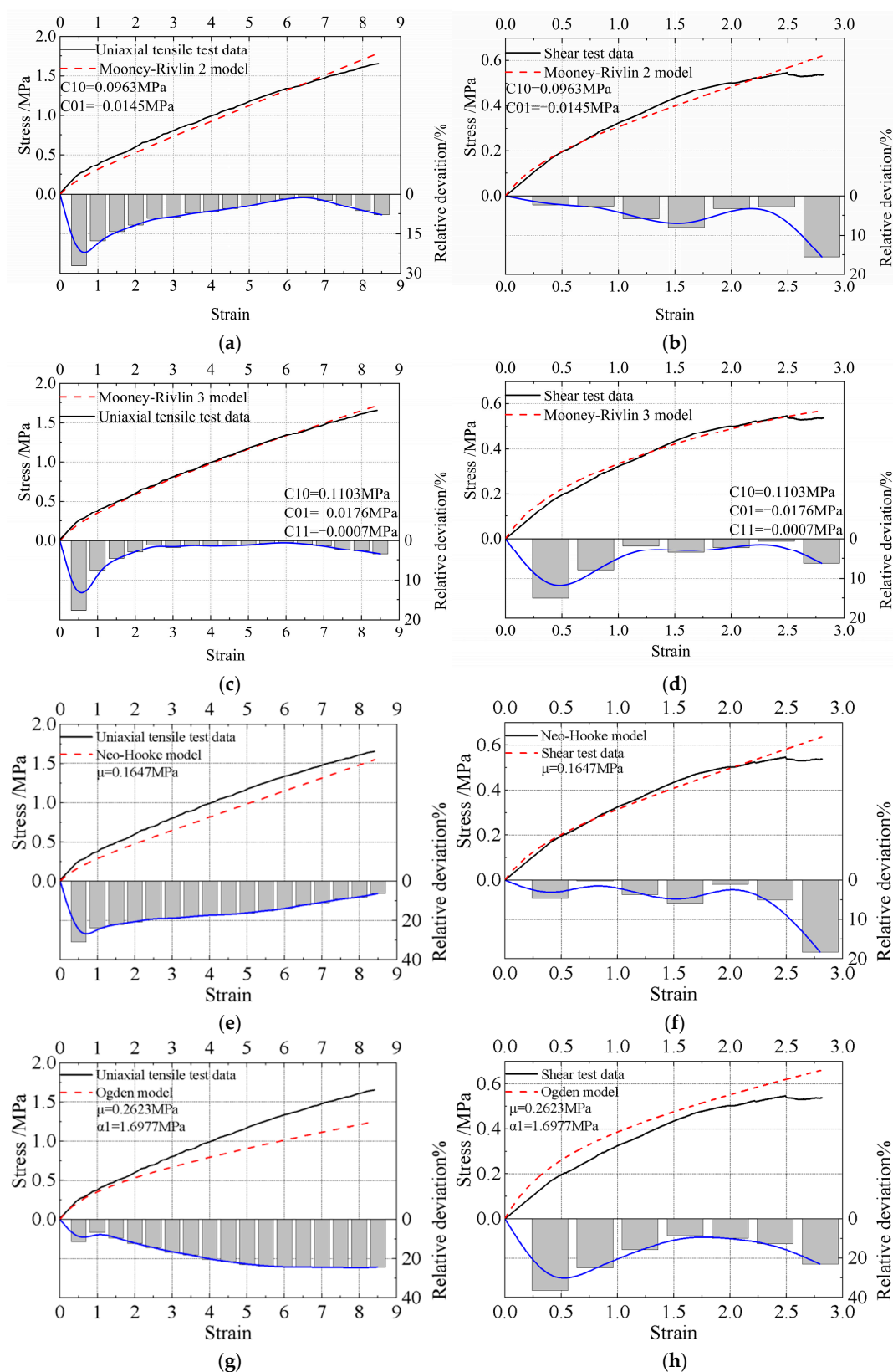


Figure 3. Typical tensile and shear stress–strain curves of the silicone sealant: (a) uniaxial tension and (b) shear.

3.2. Fitting and Evaluation of Constitutive Models

To date, more than ten applicable constitutive models have been developed for rubber hyperelasticity theory. In order to study the hyperelastic constitutive model that accurately describes the mechanical behavior of silicone structural sealant, the least squares method is widely used to obtain model parameters for the M-R2 and 3, Neo-Hookean, Ogden, and Yeoh 2 and 3 hyperelastic constitutive models. Among these, the differences between M-R2 and 3, as well as Yeoh 2 and 3, are the parameter numbers. As shown in Figure 4, the experimental data are compared with the fitting results for the silicone sealant. Moreover, the applicability of the hyperelastic constitutive model is evaluated using three indicators: goodness of fit, relative deviation, and root mean square error [29,30].



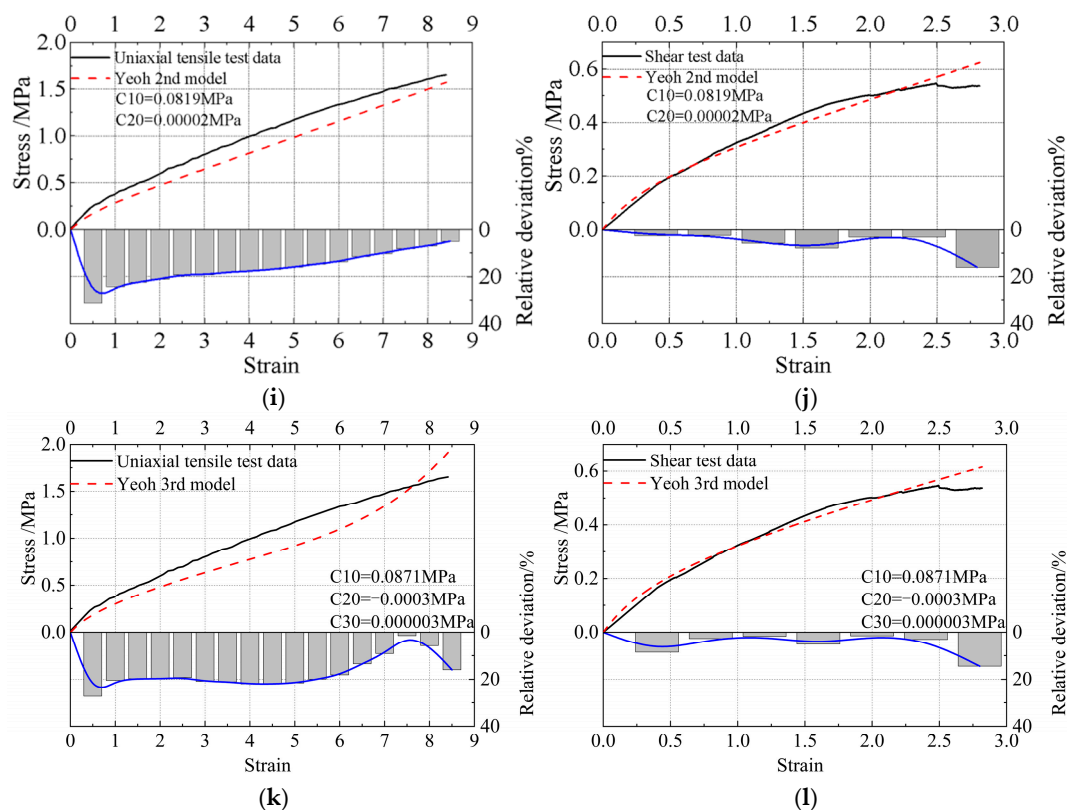


Figure 4. Comparison of experimental data with fitting results: (a) uniaxial tensile, (b) shear, (c) uniaxial tensile, (d) shear, (e) uniaxial tensile, (f) shear, (g) uniaxial tensile, (h) shear, (i) uniaxial tensile, (j) shear, (k) uniaxial tensile, and (l) shear.

3.3. Goodness of Fit

The coefficient of determination R^2 is a statistical measure of the goodness of fit. A good R^2 typically approaches 1.0, and in the context of hyperelastic constitutive modeling, values above 0.95 are often considered excellent, indicating that the model almost perfectly captures the experimental stress–strain behavior, as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^n (\mathcal{Y}_i - \hat{\mathcal{Y}}_i)^2}{\sum_{i=1}^n (\mathcal{Y}_i - \bar{\mathcal{Y}})^2} \quad (29)$$

where y_i is the experimental result, $\hat{y}_i$ is the fitting result, and $\bar{y}$ is the average of the experimental results. According to the data in Figure 4, the goodness of fit can be calculated using Equation (29), as shown in Table 2. The M-R3 model has a high level of fitting accuracy. Poor fitting accuracy is observed for the M-R2 model with shear data, as well as for the Neo-Hookean, Yeoh 2nd, and Yeoh 3rd models with tensile data. The Ogden model gives the lowest accuracy overall, while the M-R3 model shows the best fit for both tensile and shear tests.

Table 2. Coefficients of determination of models.

Model	Tensile Test	Shear Test
Mooney–Rivlin2	0.9795	0.9301
Mooney–Rivlin3	0.9963	0.9776
Neo–Hookean	0.8932	0.9221
Ogden	0.7091	0.6697
Yeoh 2nd	0.8990	0.9286
Yeoh 3rd	0.8589	0.9508

3.4. Root Mean Square Error

The root mean square error (RMSE) is calculated to evaluate the fitting accuracy. If the RMSE approaches 0, the fitting accuracy is the highest, and the calculation equation is as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (30)$$

where y_i is the experimental result, $\hat{y}_i$ is the fitting result, and n is the number of samples. According to the data in Figure 4, the RMSE can be calculated, as shown in Table 3. For the two tests, the M-R2 model and M-R3 model have lower fitting errors, but the M-R3 model has a better fitting accuracy compared to the M-R2 model. The Neo–Hookean, Yeoh 2nd, and Yeoh 3rd models demonstrated relatively larger fitting errors.

Table 3. Root mean square errors of models.

Model	Tensile Test	Shear Test
Mooney–Rivlin2	0.0654	0.0302
Mooney–Rivlin3	0.0275	0.0171
Neo–Hookean	0.1495	0.0319
Ogden	0.2469	0.1674
Yeoh 2nd	0.1454	0.0306
Yeoh 3rd	0.1719	0.0253

A single indicator cannot comprehensively evaluate the fitting accuracy of this model. Therefore, the method combining R^2 and RMSE is proposed to evaluate the fitting performance on experimental data, which is shown in Table 4. According to Table 4, the M-R3 model exhibits the best fitting accuracy for both the uniaxial tensile and shear tests, with an evaluation level of G. Therefore, the M-R3 model is selected as the constitutive model for silicone structural sealant to characterize mechanical performance.

Table 4. Comprehensive evaluation results of models.

Model	Tensile Test	Shear Test
Mooney–Rivlin2	G	N
Mooney–Rivlin3	G	G
Neo–Hookean	P	N
Ogden	P	P
Yeoh 2nd	P	N
Yeoh 3rd	P	G

Note: G indicates good fitting results; N is the general fitting result; P has poor fitting results.

3.5. Relative Deviation

The relative deviation was determined as the applicable range of each hyperelastic model, which can directly display the error size between the experimental value and the fitting value. The equation of relative deviation is as follows: A relative deviation below 10% indicates applicability, while a deviation above 10% indicates inapplicability. The optimal applicability range of each constitutive model can be obtained from Table 5.

Table 5. The applicable deformation range of each hyperelastic constitutive model.

Model	Tensile Test			Shear Test	
	Minor Deformation	Moderate Deformation	Severe Deformation	Minor Deformation	Moderate Deformation
Mooney–Rivlin2	Inapplicable	$2.50 < \varepsilon < 6$	$6 < \varepsilon < 8.41$	$0 < \gamma < 1$	$1 < \gamma < 2.59$
Mooney–Rivlin3	$0 < \varepsilon < 1$	$1 < \varepsilon < 6$	$6 < \varepsilon < 8.41$	$0 < \gamma < 1$	$1 < \gamma < 2.82$
Neo–Hookean	Inapplicable	Inapplicable	$7.31 < \varepsilon < 8.41$	$0 < \gamma < 1$	$1 < \gamma < 2.55$
Ogden	$0 < \varepsilon < 1$	$1 < \varepsilon < 1.85$	Inapplicable	Inapplicable	$1.46 < \gamma < 2$
Yeoh 2nd	Inapplicable	Inapplicable	$6.88 < \varepsilon < 8.41$	$0 < \gamma < 1$	$1 < \gamma < 2.58$
Yeoh 3rd	Inapplicable	Inapplicable	$6.98 < \varepsilon < 8.41$	$0 < \gamma < 1$	$1 < \gamma < 2.59$

Note: ε is tensile strain; γ is shear strain.

The above results indicate that the M-R3 model accurately fits the uniaxial tensile data over the entire deformation range. This is attributed to its sufficient number of terms (C_{10} , C_{01} , and C_{11}) that capture the typical strain-stiffening effect of rubber-like materials at large deformations. In contrast, the Ogden model only shows excellent accuracy at small strains (<1.85), while the Neo–Hookean, Yeoh 2nd, and Yeoh 3rd models have lower applicability in the large deformation range and are hence not recommended. For shear tests, the M-R3 model again outperforms all other models across the full shear strain range (γ up to 2.82), whereas the M-R2, Neo–Hookean, Yeoh 2nd, and Yeoh 3rd models yield reasonable fits, although only for $\gamma < 2.55$. Our results are broadly consistent with previous comparative studies on hyperelastic models for filled rubbers. For example, Wang et al. [31] also found that the M-R3 model provides the lowest overall error across combined tension and shear loading. Therefore, the M-R3 model was adopted as the constitutive model for numerical analysis of the silicone sealant.

4. Validation by Finite Element Analysis (FEA)

The uniaxial tensile and shear tests of the sealant were simulated using ANSYS Workbench FEA software (2021 R1). To simplify the simulation process, the effective length portion was intercepted for modeling, and the simplified FEA model is presented in Figure 5a. The FEA model was established on a 1:1 scale based on the shear specimen in Figure 5b. Since the specimen deformation was relatively small and would not cause failure of the adhesive-bonded interface, a tie constraint was adopted.

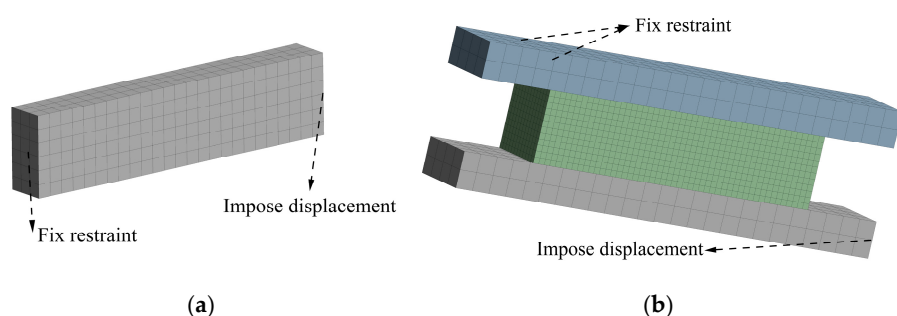


Figure 5. Finite element analysis model: (a) uniaxial tensile and (b) shear.

The finite element (FE) models for both uniaxial tensile and shear tests are discretized using tetrahedral meshes (element type: C3D10), with a unit size of 1 mm. The hyperelastic behavior of the silicone structural sealant is described by the M-R3 model, with the parameters calibrated from the experimental data, $C_{10} = 0.1103$ MPa, $C_{01} = -0.0176$ MPa, and $C_{11} = -0.0007$ MPa. The M-R3 model was selected because our previous evaluation showed that it exhibits the smallest relative deviation across the full range of tensile and shear deformations. This choice is also supported by prior work on silicone adhesives [31]. For the uniaxial tensile simulation, one end face of the specimen was fully fixed ($U_x = U_y = U_z = 0$). A displacement load of 25 mm was applied to the opposite end face at a constant rate of 10 mm/min. For the shear test simulation, the specimen was divided into three parts: two outer substrates and a middle silicone sealant layer. The substrates were modeled as a linear elastic aluminum alloy, as their deformation is negligible compared to the sealant. The sealant is again described by the M-R3 model with the same parameters. One end of the assembly was fixed, while the opposite end was subjected to a longitudinal displacement of 12 mm over 72 s.

As shown in Figures 6 and 7, the numerical simulation results of the uniaxial tensile specimen indicate that the distributions of stress and strain are relatively uniform, with a maximum stress of 0.80 MPa and a maximum strain of $0.76 \mu\epsilon$. In comparison, the shear specimen exhibits stress concentration at the edges, with a maximum stress of 1.33 MPa and a maximum strain of $0.88 \mu\epsilon$. The shear load induces more pronounced local stress and strain variations in the specimen.

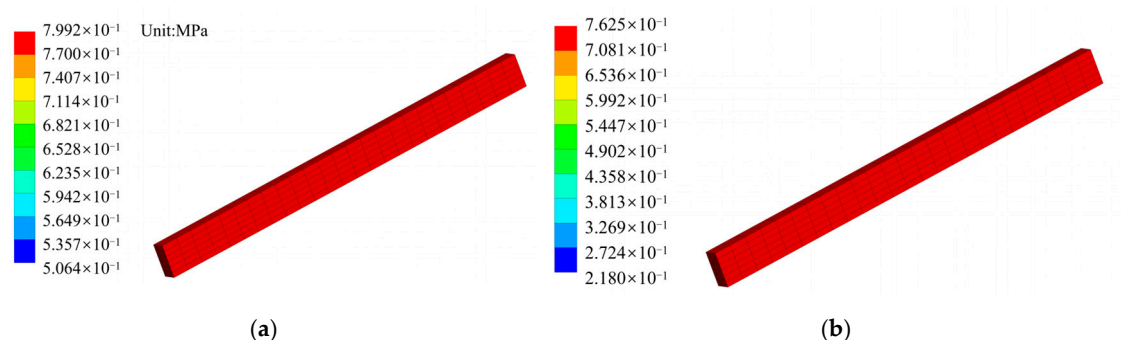


Figure 6. Uniaxial tensile test simulation analysis: (a) stress and (b) strain.

A reaction probe was applied to the center point of the loaded section to obtain force and displacement numerical simulation data, from which the relative error was calculated. As shown in Figure 8a,b, the maximum relative error between the simulation and experiment for the tensile test and shear test is 9.6%. This confirms that the M-R3 model not only satisfies the applicability criterion but also exhibits the lowest error among the considered hyperelastic models. Therefore, the M-R3 parameter model was selected as the constitutive model for the FEA of silicone sealant.

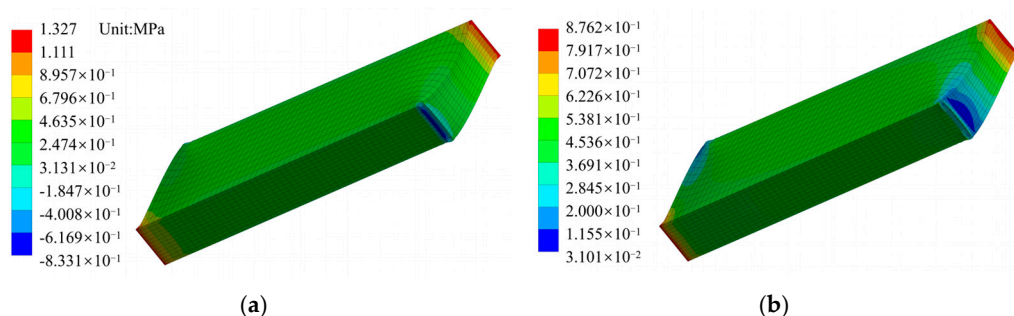


Figure 7. Shear test simulation analysis: (a) stress and (b) strain.

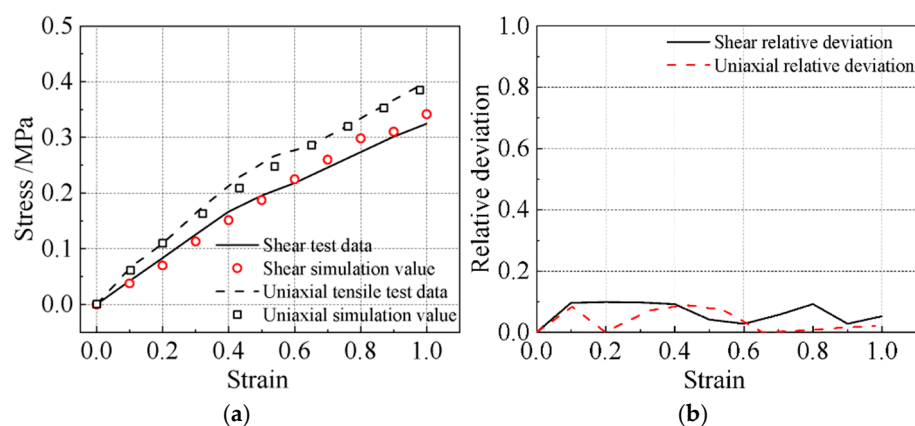


Figure 8. Comparison of test data with simulation data: (a) Shear and uniaxial test. (b) Relative deviation.

5. Mechanical Response Analysis of Glass Curtain Walls Under Wind Load

This section focuses on curtain wall panels under wind loading. The M-R3 parameter model was adopted as the constitutive model for the silicone sealant in FEA. A comprehensive numerical model of the hidden-frame glass curtain wall was established to analyze its mechanical behavior under various debonding conditions.

The numerical analysis model of the glass curtain wall structure consists of a tempered glass panel and silicone structural sealant strips. Among these, the glass panel is tempered glass with dimensions of 1000 mm × 1000 mm × 6 mm. Sealant strips were placed on both the length and width sides of the glass panel with a size of 12 mm × 12 mm. Moreover, debonding conditions were simulated by varying the length of the sealant strip. The aluminum alloy supporting frame was excluded from the analysis.

Wind-induced load, as a critical external excitation source for curtain wall systems, primarily manifests as a normally distributed load. Therefore, a uniform load of 550 Pa was applied to one side of the glass panel to simulate wind load effects. Since debonding zones are predefined during the 3D modeling phase, tied contact was selected for the connection between the glass panel and silicone structural sealant. Similarly, a tied contact was adopted for the connection between the silicone structural sealant and aluminum alloy profiles. The opposite side of the aluminum alloy profiles was fixed by constraining all translational and rotational degrees of freedom. Zhou et al. [32] successfully achieved structural sealant damage identification in hidden-frame glass curtain walls by applying static loads to panels with continuously cut sealant beads, utilizing glass panel corner rotations and deflections. Building upon this existing research and considering the influence of residual sealant on glass panel behavior, this study selected debonding location, debonding length, and debonding orientation as the control variables. Detailed parameters are listed in Table 6.

Table 6. Operating conditions.

Working Conditions	Debonding Location	Debonding Length
1	Debonding-free	Debonding-free
2	Central edge	100 mm glass-side
3	Central edge	200 mm glass-side
4	Lower edge	100 mm glass-side
5	Lower edge	200 mm glass-side
6	Central edge	100 mm aluminum frame-side

A finite element numerical analysis model of debonded hidden-frame glass curtain walls was established, and mechanical behavior under wind loads was analyzed. The displacement, stress, and strain contour plots of debonded hidden-frame glass curtain walls under various working conditions subjected to wind loads are presented in Figures 9, 10, and 11, respectively. The mid-span and maximum deflections at edges under different working conditions are demonstrated in Table 7.

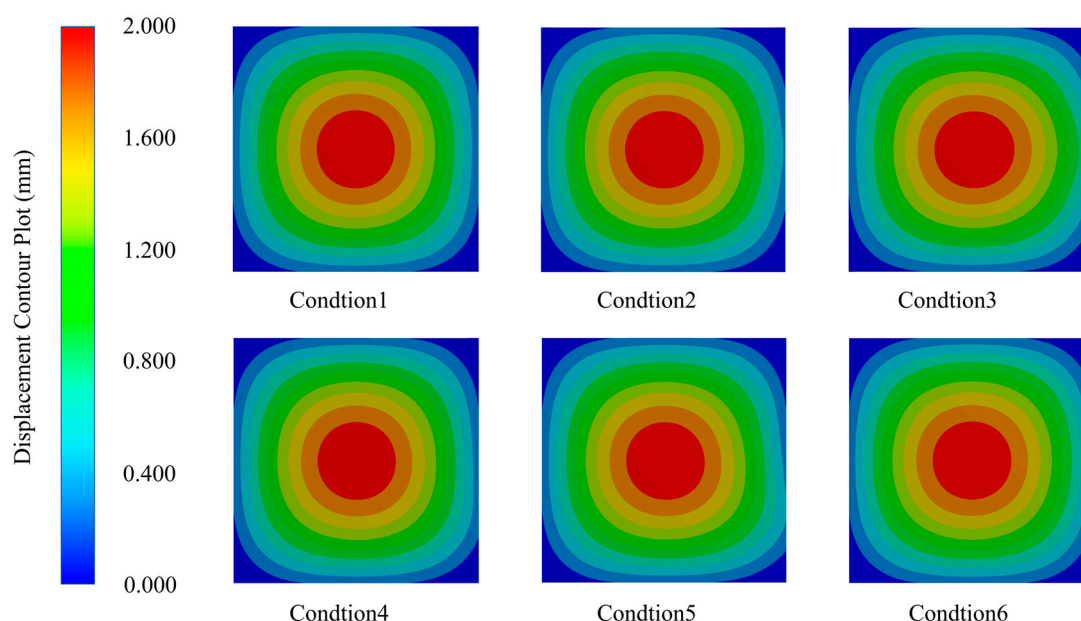


Figure 9. Displacement contour plots of debonded hidden-frame glass curtain walls.

Table 7. Deflection comparison of debonded hidden-frame glass curtain walls under various working conditions.

Working Conditions	Mid-Span Deflection/mm	Maximum Deflection at the Debonded Edge/mm
1	1.9287	0.2640
2	1.9514	0.3725
3	1.9953	0.5689
4	1.9400	0.3048
5	1.9591	0.4270
6	1.9704	0.3390

As the debonding length increases, the deflection of the glass panel gradually increases. In the displacement contour plots, the deflection contours progressively approach the debonded region, while those along the intact edge remain largely unchanged. Under negative wind pressure, for central-edge debonding, when the debonding length increases to 200 mm, the mid-span deflection increases by 0.066 mm (3.4%), and the maximum deflection at the debonded edge increases by 0.3 mm (113.6%). For lower-edge debonding, the mid-span deflection increases by 0.03 mm (1.6%), and the maximum deflection at the debonded edge increases by 0.163 mm (61.7%). This indicates that due to the restraining effect of the silicone sealant, central-edge debonding results in larger deformation than lower-edge debonding. For the case of debonding at the aluminum panel side, the mid-span deflection increases by 0.042 mm (2.2%), and the maximum deflection at the debonded edge increases by 0.075 mm (28.4%), indicating that the debonding direction has a limited effect on the behavior of the structurally glazed curtain wall panel under negative wind pressure.

As shown in Figure 10, under negative wind pressure, the maximum strain of the debonded panel occurs at the center and gradually increases with increasing debonding length. For central-edge debonding, when the debonding length increases to 200 mm, the maximum strain increases by $2.3 \mu\epsilon$ (4.7%). For lower-edge debonding, the maximum strain increases by $7.3 \mu\epsilon$ (15%). Compared with the non-debonded condition, the stress–strain level rises and the contour lines begin to shift. When the debonding length remains constant, the debonding location has a minimal effect on the in-plane stress–strain distribution but significantly affects the stress concentration at the debonded edge. When debonding occurs, under negative wind pressure, the variation in the maximum strain at the center of the glass panel is relatively small, whereas the strain variation at the debonded edge is substantial. Accordingly, the following investigation was conducted.

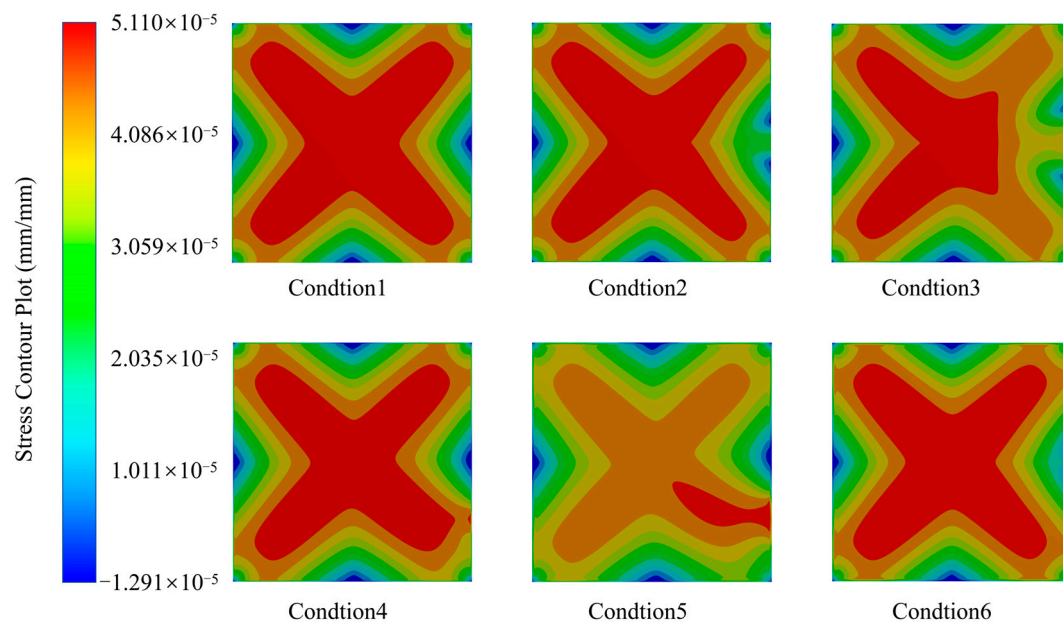


Figure 10. Strain contour plots of debonded hidden-frame glass curtain walls under various working conditions.

Figure 11 is the strain distribution at the midpoints of all four edges of debonded hidden-frame glass curtain walls under various working conditions. The strain values at the debonded edge are greater than those at the other three unbonded edges, and they gradually increase as the debonding length increases. When debonding occurs in the central-edge region with a length of 200 mm, the maximum tensile strain is $40.1 \mu\epsilon$ in condition 3. Comparatively, the maximum compressive strain is $9.2 \mu\epsilon$ in condition 5. For glass panel edges without debonding, the trend of strain on their three sides remains consistent in condition 1.

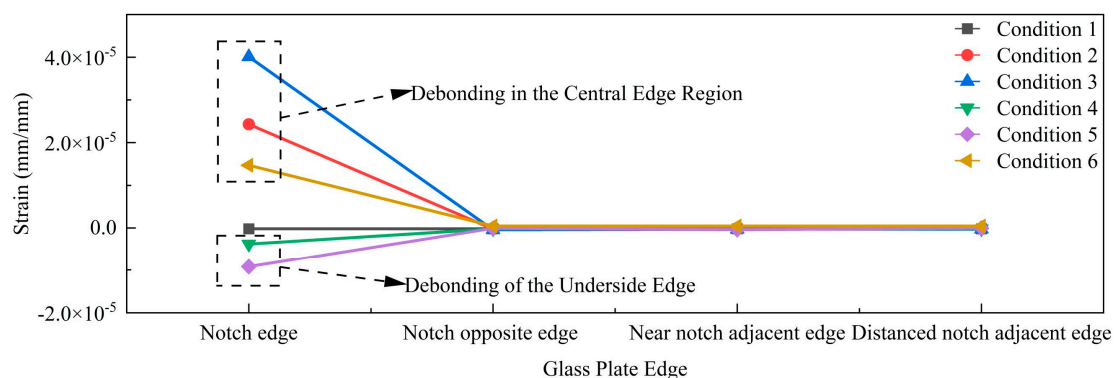


Figure 11. Strain distribution at midpoints of all four edges of debonded hidden-frame glass curtain walls under various working conditions.

6. Conclusions

This study systematically investigates the hyperelastic constitutive modeling of silicone structural sealants and their application in the FEA of glass curtain walls. In this paper, the conclusions can be summarized as follows.

- (1) The improved comprehensive fixture of silicone structural sealants is produced for both tensile and, particularly, shear tests. The M-R3 model demonstrates the best fitting performance, which is comprehensively evaluated by three indicators (goodness of fit, root mean square error, and relative deviation).
- (2) The M-R3 model is used to establish a finite element model of the silicone structural sealant to simulate uniaxial tensile tests and shear tests. The results show that, compared with tensile loading, shear loading induces more pronounced local stress and strain variations in the specimen. The maximum relative error is 9.6%, demonstrating good agreement.
- (3) The mechanical response of the glass curtain wall under wind load is simulated. The results show that debonding of the silicone sealant significantly affects the stress and strain of the glass, including both the location and length of the debonding. Under condition 3, the maximum tensile strain reaches $41.1 \mu\epsilon$.

This study presents a shear-effect-based constitutive model for silicone sealant, uncovers the failure evolution behavior of silicone structural sealant in glass curtain walls under wind load, and offers a reference for curtain wall structural design and maintenance.

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Abbreviations

The following abbreviations are used in this manuscript:

FEA Finite element analysis

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