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Original Article

Effect of viscoelasticity on stiffness prediction for the bi-adhesive single lap joints

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ABSTRACT

Although the stress analysis of the adhesively bonded single lap joints(SLJ) has been studied in many papers there are limited investigations upon stiffness prediction of the adhesively bonded joints. There is also no study on the viscoelasticity effect on stiffness prediction of the SLJ in the open literature. In this study an analytical model was proposed for the stiffness prediction of the bi-adhesive SLJ with use of two types of adhesives SikaFast 5215 NT and SikaPower 4720 as flexible and stiff adhesives, respectively. Bond-length ratio as a definition of the ratio of flexible adhesive length to stiff adhesive length was taken as d=0.2, 0.5, 1 and 2. Bi-adhesive and mono adhesive results were compared. It was concluded that the joint stiffness can be strongly affected by the stiff adhesive proportion of the overlap length. Due to time dependent elasticity modulus as a result of viscoelastic properties of adhesives, joint stiffness reduces while time progresses. Results showed that adhesive stresses and joint stiffness can be optimized by using bi-adhesive joint with an appropriate bond-length ratio. The adherend material effect was also studied. It was concluded that the adherend material strongly affects the stiffness of the joint.

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INTRODUCTION

Structural adhesives have been used in a wide range of usage areas in automotive, aerospace and naval industries. Most of the applications are mono adhesive joints due to easy applicability and adhesively bonded joints are generally exposed to peel and shear stresses. Investigations show that the stresses at the ends of the overlap length is being maximum on a mono adhesively SLJ because of the stress concentration. To reduce the stress concentration at the ends of the overlap length, functionally graded adhesive technique has been widely used in the adhesively bonded joints. A primitive version of this functionally graded adhesive layer technique is using bi-adhesive joint. In this technique, stiff adhesive is located in the middle and flexible adhesive at the ends of the overlap length. Investigations show that this technique reduces stress concentrations effectively at the ends of the overlap length.

One of the most known and first analytical stress analysis of bonded joints is 'shear lag model' which developed by Volkersen [1]. In this study shear stress distribution was given by analytically but the bending effect was ignored.

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Table 1. Elastic properties of adherends

	Modulus of elasticity (MPa)	Poisson's ratio (-)	Tensile yield strength (MPa)	Tensile strength (MPa)
Steel (S235 JR)	207000	0.3	235	370
Aluminum (7075)	71700	0.33	105	225

Considering the bending effect of bonded joints closed form shear and peel stress distributions were first given together by Goland and Reissner [2]. The earliest study for investigation of the stress analysis of the bi-adhesive joint was studied by Raphael [3]. Raphael' s study was based on Volkersen' s shear lag model and similar to this method and gave only the shear stress distribution at the overlap region. Carbas et al. [4] studied the shear stress distribution of an SLJ modeled with a functionally graded adhesive. They compared the strength of joint that modeled with functionally graded adhesive with those in which classical homogenous linear elastic adhesive used fully at the overlap region. They concluded that the strength of joint modeled with functionally modified adhesive is higher than the homogenous linear elastic adhesive model. Özer and Öz [5] compared shear and peel stress distribution of a double lap joint(DLJ) both for mono and bi-adhesive bondlines by using 3D finite element method(FEM). They showed that the stress components at the ends of the overlap region can be dramatically reduced by using bi-adhesive instead of mono models. They proved that stress components can be optimized by using appropriate bond-length ratios. Similarly Kong et. al. [6] performed FEM analysis of a bi-adhesive joint. They concluded that the stress optimization was able to enable by using appropriate bond-length ratios. Different adherend material effects considering the temperature were studied by Da Silva and Addams [7]. They proved that bi-adhesive bondline performance is better than the mono models for high temperature strength. First known viscoelastic analysis of adhesively bonded joints was performed by Delale and Erdoğan [8]. Considering the time effect, peel and shear stress distribution along the bondline were derived by using classical Laplace transform technique. Their study showed that not only peel stress was higher than the shear stress but also speed of peel stress relaxation was slower than the shear stress relaxation. Shishesaz and Reza [9, 10] studied the creep response of adhesively bonded SLJ and DLJ that were only forced to expose shear stress. They assumed adherend material and adhesive as linear elastic and three parameter viscoelastic material, respectively. They derived closed-form shear stress and strain distribution with respect to time. They found that the ratio of adhesive viscous modulus to adhesive shear modulus has an adverse effect.

Adhesives are preferable in many industrial areas due to their easy applicability and cost advantage. Many of industrial applications like automotive, aerospace, naval etc. need to be in a high rigidity according to total stiffness when compared to classical fastening methods. Despite of the stress investigations have been done in open literature in many papers there is a very limited investigation about the stiffness behavior of bonded joints. Pearson [11] investigated the effects of parameters like adherend and adhesive thickness, unsupported length, overlap length, width, material type of adhesive and adherend of the SLJs. He concluded that adherend thickness, adherend modulus and unsupported length of the joint had a strong influence on stiffness. On the contrary, joint was insensitive to width and less sensitive to adhesive modulus when compared to substrate material properties. Kumar and Pandey [12] derived a simple analytical expression for prediction of an SLJ both for mono-stiff and bi-adhesive joints. He calculated the stiffness reduction at bi-adhesive joints instead of using mono-stiff one. Another study to predict the bi-adhesive stiffness was done by Zhao [13]. Owens and Sullivan [14, 15] derived an analytical expression to predict the stiffness of an SLJ which consists of an aluminum and a composite adherend in joint structure. Then, they validated the analytical results by an experimental study. They concluded that the theoretical results close to experimental ones. These studies neglect the viscoelastic effects of adhesives while determining the total stiffness of the bonded joint.

Main motivation of this study is to find an expression for predicting the stiffness while considering the time effect due to viscoelastic properties of the adhesives. For this purpose, an SLJ joint was investigated and subjected to a tensile load by considering only axial displacements occur. Adherend material was considered as linear elastic. First of all, steel adherend was used then results were compared with those in which results of fully aluminum adherend SLJ. On the other hand, adhesives were considered as linear viscoelastic. Three parameter Maxwell-Wiechert viscoelastic model was used to define adhesive material. All investigations were done and compared for both mono and bi-adhesive joints. For bi-adhesive models bond-length ratios were considered as d=0.2, 0.5,1 and 2.

MATERIAL AND METHODS

A single lap joint was used to model the bi-adhesive bonded structure. Steel and aluminum materials which considered as linear elastic were used in SLJs. Table 1 shows the properties of adherend materials.

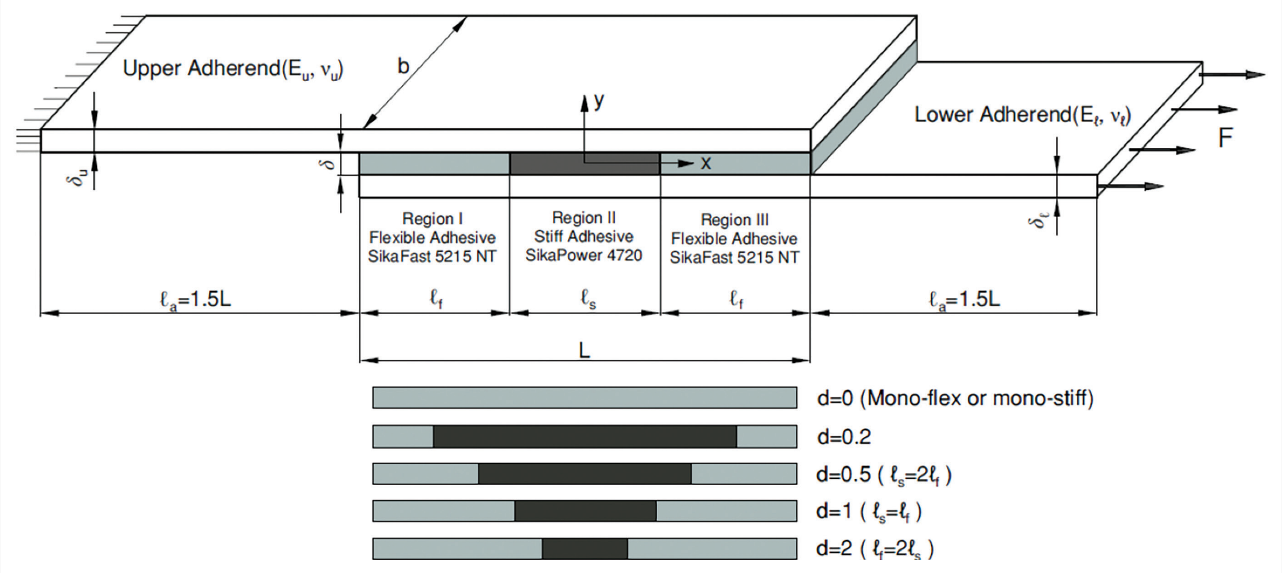


Figure 1. Basic geometry of mono and bi-adhesive single lap joint.

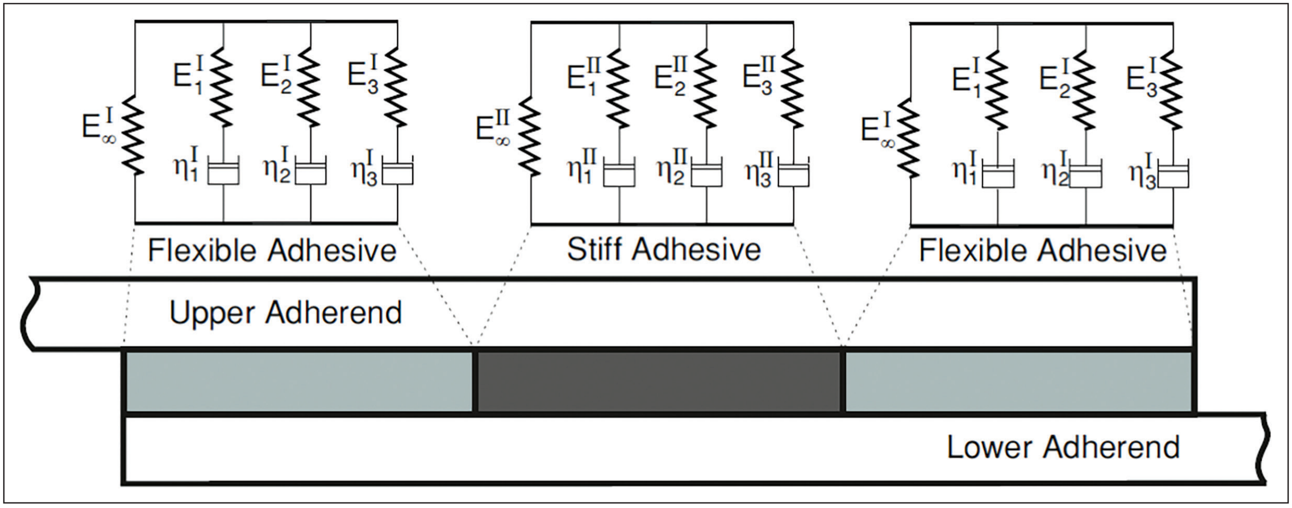


Figure 2. Three parameter Maxwell-Wiechert viscoelastic model.

SLJ total stiffness which consists of similar steel and aluminum adherends were calculated respectively. Figure 1 shows the basic geometry of a single lap joint with the use of bi-adhesive. Upper and lower adherends are fully identical and have a thickness of $\delta_u=\delta_\ell=1$ mm. E and ν refer to the modulus of elasticity and Poisson' s ratio, respectively. Subscripts u and ℓ correspond to the upper and lower adherends, respectively. Adhesive thickness is δ=0.25 mm. Total overlap length is L=20 mm and the unsupported length was taken as $\ell_a=1.5L=30$ mm. Width of the joint is b=40 mm. F is the force acting from one side of the joint. Bond-length ratio for the bi-adhesive joint is defined as $d=\ell_f/\ell_s$. Subscripts f and s correspond to the flexible and stiff adhesives, respectively. In this study four different bond-length ratios were considered and taken as d=0.2, 0.5, 1 and 2. Due to fully use of a stiff or flexible adhesive along the overlap region that means the joint is mono adhesive joint and represented as d=0.

SikaFast 5215 NT and SikaPower 4720 adhesives were used at the overlap region. Figure 1 shows that bondline is splitted into three regions for bi-adhesive joints. Region I and III are fully identical so all the adhesive properties of these regions are the same. SikaPower 4720 was located in the middle of the bi-adhesive bondline. At the ends of the overlap, the flexible adhesive SikaFast 5215 NT was located. Adhesives were considered as linear viscoelastic polymeric materials. For defining the viscoelastic properties of the adhesives, three parameter Maxwell-Wiechert viscoelastic model was used. Figure 2 shows the viscoelastic material model.

Table 2. Viscoelastic properties of adhesives

	Poisson' s ratio (-)	$E_0^{I,II}$ (MPa)	$E_\infty^{I,II}$ (MPa)	$E_1^{I,II}$ (MPa)	$E_2^{I,II}$ (MPa)	$E_3^{I,II}$ (MPa)	$\eta_1^{I,II}$ (MPa.s)	$\eta_2^{I,II}$ (MPa.s)	$\eta_3^{I,II}$ (MPa.s)
SikaFast 5215 NT	0.371*	467	81	151	140	94	104	1567	25190
SikaPower 4720	0.367*	2700	1917	249	301	233	183	3640	89794

*: Poisson' s ratio of adhesives were taken from [17, 18].

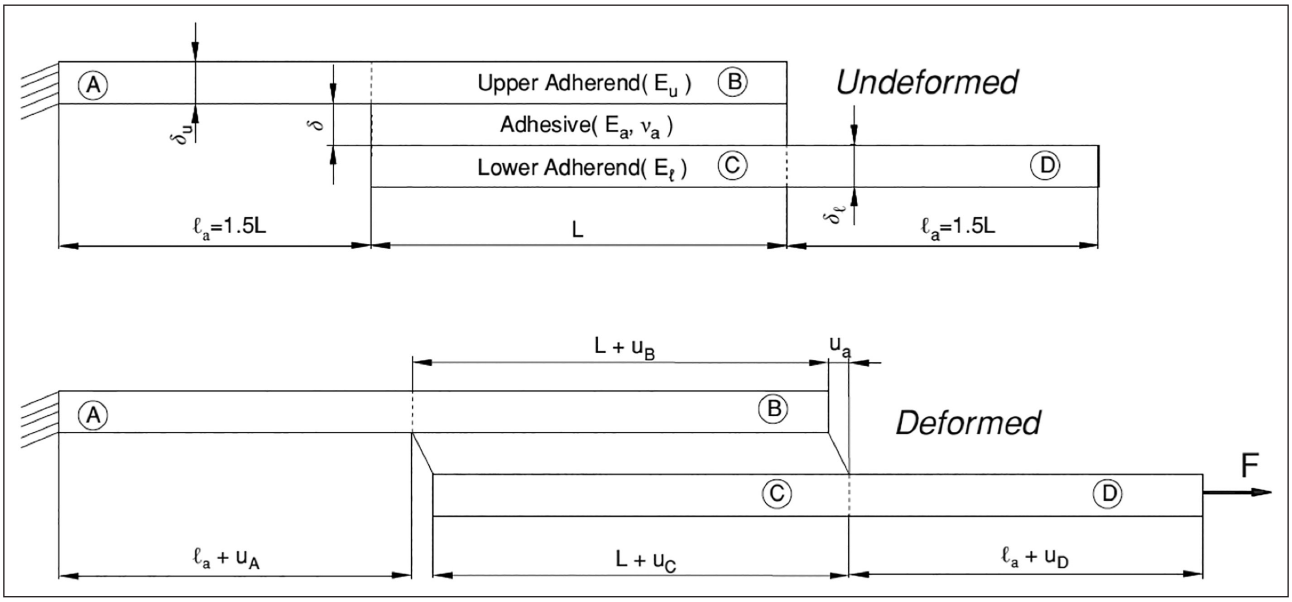


Figure 3. Undeformed and deformed case of the joint.

In Figure 2, E and η show the spring and damper coefficients of the adhesives, respectively. Superscripts I and II refer to the regions of the overlap length. Subscripts 1,2 and 3 show the sequence of the spring or damper coefficients. E_∞ defines the long-term modulus of elasticity of the adhesives. Table 2 summarizes the viscoelastic properties of the adhesives SikaFast 5215 NT and SikaPower 4720 due to the experimental study of Karlsson [16]. E0 shows the calculated modulus of elasticity according to experimental tests.

Adherends and adhesives are only allowed to axial displacements. Figure 3 shows the undeformed and deformed case of the joint under the tensile load, respectively.

The total stiffness k of the joint can be expressed as follows:

$$\mathrm{k} = \frac{F}{\Delta u} \tag{1}$$

Δu and u refer to total displacement and displacements of the splitted parts of the joint, respectively. As seen in Figure 3, the joint was splitted into four regions and Δu can be defined as follows:

$$\Delta u = u_A + u_C + u_a + u_D \tag{2}$$

In Eq. 2, u_A and u_D show the unbonded part deformations of the adherends, u_C shows the bonded part deformation of the adherend. At the last, symbol u_a refers to the axial deformation of the adhesive. Subscript a refers to the adhesive. From elasticity theory, deformations of the unbonded parts of the adherends can be written as:

$$u_A = \frac{1.5FL}{\delta_u b E_u}, \qquad u_D = \frac{1.5FL}{\delta_\ell b E_\ell} \tag{3}$$

Similarly to Eq. 3, one can write the displacement of the adherend part shown as C as follows:

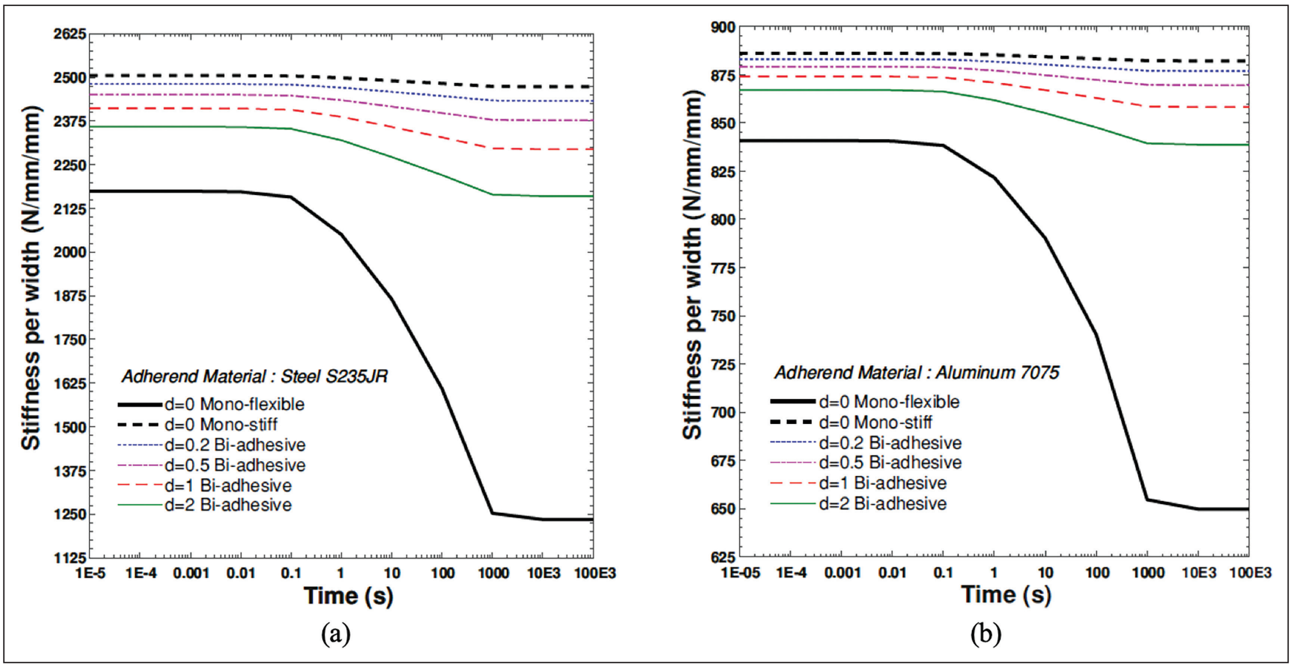
$$u_C = \frac{FL}{\delta_\ell b E_\ell} \tag{4}$$

From the definition of the shear strain, the adhesive shear strain γ can be written as:

$$\gamma = \frac{\tau}{G_a} = \frac{u_a}{\delta} \tag{5}$$

In Eq. 5, Ga shows the shear modulus of the adhesives and can be expressed as:

$$G_a = \frac{E_a}{2(1+\nu_a)} \tag{6}$$



(a) (b)

Figure 4. Time dependent stiffness prediction of joint. **(a)** Adherend material: Steel S235 JR and **(b)** Adherend material: Aluminum 7075.

Considering the average shear stress, τ can be expressed by the following:

$$\tau = \frac{F}{bL} \tag{7}$$

Substituting Eqs. 6 and 7 into Eq. 5 yields:

$$u_a = \frac{2F\delta(1+\nu_a)}{bLE_a} \tag{8}$$

Combining the Eqs. 3, 4 and 8 we can obtain the expression below:

$$\Delta u = \frac{1.5FL}{\delta_u bE_u} + \frac{FL}{\delta_\ell bE_\ell} + \frac{2F\delta(1+\nu_a)}{bLE_a} + \frac{1.5FL}{\delta_\ell bE_\ell} \tag{9}$$

Knowing that the adherends are fully identical Eq. 9 can be rewritten as:

$$\Delta u = F\left[\frac{4L}{\delta_\ell bE_\ell} + \frac{2\delta(1+\nu_a)}{bLE_a}\right] \tag{10}$$

Substituting Eq. 10 into Eq. 1 and after some manipulations, the stiffness for mono adhesive joint can be written as:

$$k_{mono} = \frac{b}{L\left[\frac{4}{\delta_\ell E_\ell} + \frac{2\delta(1+\nu_a)}{L^2E_a}\right]} \tag{11}$$

For the bi-adhesive joints, the equivalent modulus of elasticity can be arranged as [12]:

$$E_{eq} = \frac{2E_f\ell_f + E_s\ell_s}{L} \tag{12}$$

Finally, we can get the expression of the total stiffness for the bi-adhesive by writing E_{eq} instead of E_a in Eq. 11;

$$k_{bi-adhesive} = \frac{b}{L\left[\frac{4}{\delta_\ell E_\ell} + \frac{2\delta(1+\nu_a)}{L^2E_{eq}}\right]} \tag{13}$$

To find an expression of the time dependent stiffness due to viscoelastic properties of the adhesives which causes to stress relaxation, the time dependent modulus of elasticity for adhesives called as relaxation modulus, can be expressed as [19]:

$$E_a(t) = E_{f,s}(t) = E_\infty + \sum_{j=1}^{3} E_j e^{-t.E_j/\eta_j} \tag{14}$$

In Eq. 14, t refers to time. To find the relaxation modulus of the flexible or stiff adhesive, appropriate spring and damper constants have to be taken from Table 2. Finally, time dependent stiffness can be expressed as follows by using Eqs. 11, 13 and 14;

$$k_{mono}(t) = \frac{b}{L\left[\frac{4}{\delta_\ell E_\ell} + \frac{2\delta(1+\nu_a)}{L^2E_a(t)}\right]}, \quad k_{bi-adhesive}(t) = \frac{b}{L\left[\frac{4}{\delta_\ell E_\ell} + \frac{2\delta(1+\nu_a)}{L^2E_{eq}(t)}\right]} \tag{15}$$

where

$$E_{eq}(t) = \frac{2E_f(t)\ell_f + E_s(t)\ell_s}{L} \tag{16}$$

RESULTS AND DISCUSSION

Time dependent stiffness predictions were presented in Figure 4. Stiffness predictions are carried out by using two types of adherends. Figure 4a shows the stiffness predictions of the joint with the adherend S235 JR steel; Figure 4b shows stiffness predictions of the joint with the adherend 7075 aluminum.

Table 3. Stiffness prediction for mono and bi-adhesive joints by using steel and aluminum adherends

			Steel adherends S235 JR Joint stiffness (N/mm/mm)			Aluminum adherends 7075 Joint stiffness (N/mm/mm)		
Joint type	d	Bondline configuration (mm)	t=0	t=10E3 s	Stiffness drop (%)	t=0	t=10E3 s	Stiffness drop (%)
Mono-flexible	0	20	2174	1235	43.2	841	650	22.7
Mono-stiff	0	20	2505	2473	1.3	886	882	0.45
	0.2	2.86–14.29–2.86	2481	2433	1.9	883	877	0.68
Bi-adhesive	0.5	5-10-5	2450	2377	3.0	879	870	1.0
	1	6.67–6.67–6.67	2411	2294	4.9	874	858	1.8
	2	8–4–8	2359	2160	8.4	867	839	3.2

From Figure 4a, it can be clearly seen that the highest drop in stiffness is observed at mono-flexible joint with the fully flexible adhesive SikaFast 5215 NT over the overlap length by almost 43.2% from t=0 to t=10E3 s. After the time t=10E3 s the stiffness remains constant because of creep properties of adhesives. However, the least drop in stiffness is observed at mono-stiff joint with the fully stiff adhesive SikaPower 4720 over the overlap region as 1.3%. On the other hand, the bi-adhesive joint stiffness are influenced strongly due to the amount of stiff adhesive used over the bond-length. Although the high stiffness drop at mono-flexible joint the bi-adhesive joint with bond-length ratio of d=2, which has the minimum amount of stiff adhesive in the overlap to those of the other bond-length ratios, has a stiffness drop as 8.4%. Increasing the amount of stiff adhesive reduces the stiffness drop of bi-adhesive joint. For instance, bi-adhesive joint with the bond-length ratio of d=0.2 which has the maximum amount of stiff adhesive at the overlap region has a stiffness drop of 1.9%.

Figure 4b shows the stiffness prediction by using of aluminum adherends in the joint. General stiffness behaviour of the joint with aluminum adherends shows the similar stiffness tendency of steel adherend joint. Stiffness drops of the mono-flexible and mono-stiff joints were calculated as 22.7% and 0.45%, respectively. Similarly the stiffness drops for the bi-adhesive bond-length ratios of d=0.2 and 2 are 0.68% and 3.2%, respectively.

Table 3 summarizes the stiffness predictions of all the joints with respect to time for the mono and bi-adhesive configurations by considering different adherend materials.

It can be seen that the stiffness of the bi-adhesive SLJ is increasing with decreasing of the bond-length ratio which means increase of the amount of the stiff adhesive. On the other hand, stiffness drop of steel adherend SLJ with respect to time is more than the aluminum adherend SLJ. This result can be attributed to modulus of elasticity difference of steel and aluminum materials. It can be expected that low displacements occur in the steel adherends due to high rigidity of the steel and this causes more deformations at the overlap region. High rigidity of the steel adherends make joint more sensitive to time effect because of the high adhesive deformations.

CONCLUSION

In this study, time dependent stiffness behavior of the mono and bi-adhesive SLJs were investigated analytically by considering the adherends and adhesives as linear elastic and linear viscoelastic, respectively. For bi-adhesive joints, four different bond-length ratios were studied and compared with mono-flexible and mono-stiff joints. Followings can be concluded from the obtained results:

1. Stiffness behavior of the joint was strongly assigned by stiff adhesive SikaPower 4720.
2. Stiffness values of the bi-adhesive joints with the lower bond-length ratios got closer to the stiffness of the mono-stiff joint with the full of stiff adhesive over the full length of bondline.
3. Maximum stiffness of the bi-adhesive joints was observed at d=0.2 bond-length ratio.
4. All the bonding configurations including mono and bi-adhesive had a tendency of lowering stiffness with respect to time. Most stiffness drop was observed for the mono-flexible type of joint. However, the least stiffness drop was observed for the mono-stiff bondline. Regardless of the adherend material type, stiffness difference between the mono-stiff and bi-adhesive joints with low bond-length ratio is very small.
5. Adherend material has an important effect on the total stiffness behavior of the joints. Total stiffness of the joint with the aluminum adherend is lower than the steel adherend joints due to the modulus of elasticity of adherend materials.
6. Joints with aluminum adherends has a lower stiffness drop with respect to time when compared to steel adherend joints. This result can be explained by the high rigidity of steel material. Because of the high rigidity of the steel adherend, lower displacements occur at the ad-

herends. However, high adhesive displacements occur at the joint and causes more stiffness drop.

7. Considering the time effect, it was seen that the bi-adhesive joints can be used to reduce the stresses and ensuring the stiffness.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Mustafa Çay: Conceptualization, methodology, investigation, writing, original draft preparation.

Halil Özer: Writing, reviewing and editing the paper.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

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