

Modelling of Damping in Small Satellite Structures Incorporating Bolted Joints

Rui Wang, Andrew D. Crocombe
 School of Engineering, University of Surrey
 Guildford, Surrey, GU2 7XH, UK; (+44) (0)1483 686563
 r.wang@surrey.ac.uk, a.crocombe@surrey.ac.uk

Guy Richardson
 Surrey Satellite Technology Ltd.
 Guildford, Surrey, GU2 7XH, UK; (+44) (0)1483 683754
 g.richardson@sstl.co.uk

Craig I. Underwood
 Surrey Space Centre, University of Surrey
 Guildford, Surrey, GU2 7XH, UK; (+44) (0)1483 689805
 c.underwood@surrey.ac.uk

ABSTRACT: The energy dissipating capability of bolted joints in a small satellite was investigated using Finite Element (FE) analysis. It was found the energy dissipating capability of the bolted joints operating in the micro-slip region was quite low. The idea of using viscoelastic layer in the bolted joints was introduced to improve the energy dissipation.

There are some good constitutive models for viscoelastic materials. However, they cannot be used to model the viscoelastic layer in the satellite because the dimension of the joints and the layers are too small. A spring dashpot joint model was created and extended into the non-linear domain to overcome this problem.

Experiments were carried out on different viscoelastic materials. The results were used to determine the properties of spring dashpot systems. Different formulations of stiffness and damping were investigated and optimised to fit the numerical results to the test data. Good correlation was obtained between the models and the data. The spring-dashpot joints were used in a simple satellite model to investigate the effect of joints on the satellite response. This damping design was quite effective in decreasing the response of the satellite structure when it experienced harsh environments like launch.

1. INTRODUCTION

In a small satellite developed by Surrey Satellite Technology Ltd. (SSTL) a lot of bolted joints were used to connect the honeycomb panels in the construction of the main body of the spacecraft. This made manufacture, assembly and design easier.

Much research has been undertaken investigating the behaviour of bolted joints. It was found that a bolted joint under shear force developed two states: micro-slip, (which happens when parts of the contact surfaces have relative movement) and macro-slip, (which happens when the whole contact surfaces move relative to each other). The FE method has become a very important tool for bolted joint analyses. Most bolted structures need a new analysis because the behaviour of the structure is different due to different configurations and properties of joints¹⁻⁴.

In this paper there are two parts. The first part is about the energy dissipation estimation of a satellite structure with plain bolted joints, (that is, the jointing

parts are connected by bolts and nuts directly without any damping materials between them). It is being published in another paper⁵ and will be discussed very shortly here. The second part is about the same subject but the joints have viscoelastic layers in them.

In the first part, a detailed bolted joint model was created to establish the relationship between the force and energy dissipated in a joint. The joint parameters used are set on the real satellite joint. The forces in the satellite joints were derived from a satellite model. The force-energy relationship was used for these forces to obtain the energy dissipated by all the joints. All the joints operated in the micro-slip state in the real satellite. At this condition it was found the energy dissipated in the joints is only a small part of the energy input to the satellite.

In the second part, a viscoelastic layer was used in the joints to improve the energy dissipating capacity. There are many materials whose behaviour lies between an elastic solid and a viscous liquid. These are called viscoelastic materials. They have attracted

attention for long time. Many have been used as dampers⁶⁻¹⁰. The modelling of the bolted joints with viscoelastic layers were investigated in this paper. A spring-dashpot model was established and analysed. However, as many researchers have pointed out, this material is both strain and strain rate dependent¹¹⁻¹³. A non-linear spring dashpot model has been created to take this into account.

The energy dissipation of a satellite with and without spring dashpot systems was compared. It was found that the viscoelastic layer improved the energy dissipation considerably and could be considered for use in the future satellite design.

2. ANALYSING ENERGY DISSIPATION IN PLAIN BOLTED JOINTS OF SPACECRAFT STRUCTURES

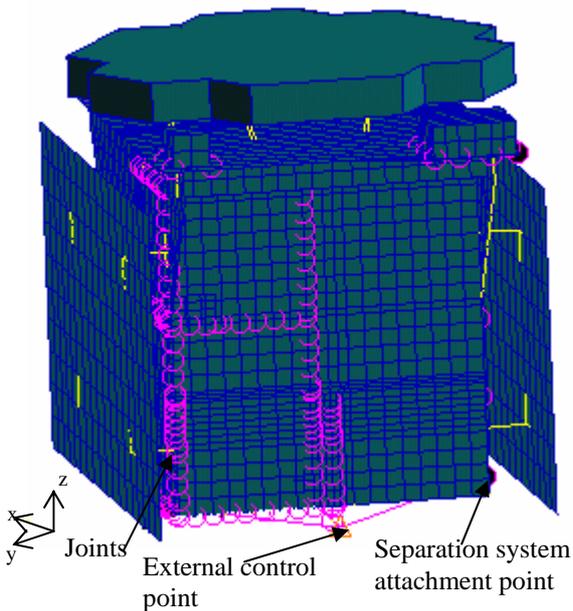


Figure 1. Satellite Model

Figure 1 shows a FE model of the satellite. The joints lie on the lines indicated by the circles. There are two kinds of joints under consideration: one connecting the panels lying in the same plane (plane joints), another connecting panels perpendicular to each other at one end (corner joints). The FE nodes on connected panels were jointed together using multipoint constraints (MPC). These ensure that the nodes have the same translational displacements. The forces in the bolted joints were taken as the MPC forces. On the bottom of the model, four stiff springs were used to represent the separation system attachment. The energy input to the satellite was calculated from the area of the four force-displacement hysteresis loops at the attachment points.

A detailed joint model of a plane joint, shown in Figure 2, was created. Due to symmetry, only a quarter of the joint is modelled. By undertaking static

analyses it was found that the force and energy relationship (in micro-slip) could be represented as a fourth order polynomial:

$$E = 0.0005F^4 + 0.0009F^3 + 0.0013F^2 + 0.0031F + 0.0023 \quad (1)$$

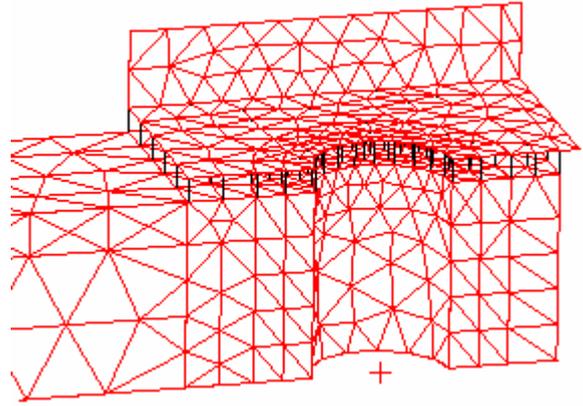


Figure 2. Detailed Joint Model

The corner joints are different from the plane joints. By comparing the two kinds of joints the energy dissipated in the corner joints are taken as:

$$E = 0.0002F^4 + 0.0004F^3 + 0.0007F^2 + 0.0016F + 0.0012 \quad (2)$$

Table 1. Percentage of Energy Dissipated from Joints to Input Energy

	f1	f2	f3	f4	f5	f6
x excitation	3.1	1.5	0	0	.45	1.4
y excitation	2.9	1.6	.37	.30	1.0	1.6
z excitation	2.0	2.1	1.6	1.6	.83	.39

FE frequency response analyses were carried out on the complete satellite structure (Figure 1). The forces at six key natural frequencies in each excitation direction were derived. Formula (1) and (2) were used to calculate the energy dissipated in all joints. The ratio of the energy dissipated from all these joints to the excitation input energy was calculated. It varied with structural damping coefficient c_s and excitation level a . A smaller c_s or a smaller a caused the ratio to increase. The percentage of the energy dissipated in frictional damping at a level of c_s of 0.04 and a of $2g$ (g is the gravity acceleration) is shown in Table 1.

It can be seen from Table 1 that the energy dissipated in plain bolted joints were quite small. Thus, the use of viscoelastic material in the joints to increase the damping was investigated next.

3. DAMPING IN BOLTED JOINTS WITH A VISCOELASTIC LAYER

3.1 Typical Properties of a Viscoelastic Material

Researchers have used a variety of techniques to represent the properties of viscoelastic materials. A common way to achieve this is to define the viscoelastic material using a complex modulus.

$$G^* = (1 + i\eta)G \quad (3)$$

The real part of the modulus represents the stiffness of the material and is called the storage modulus (G). The imaginary part represents the damping of the material and is called the damping modulus. The ratio of damping modulus to storage modulus is called the loss factor (η). Both η and G are temperature and frequency dependent. Figures such as the one in figure 3 for SMRD 100F90 have become an industry standard.

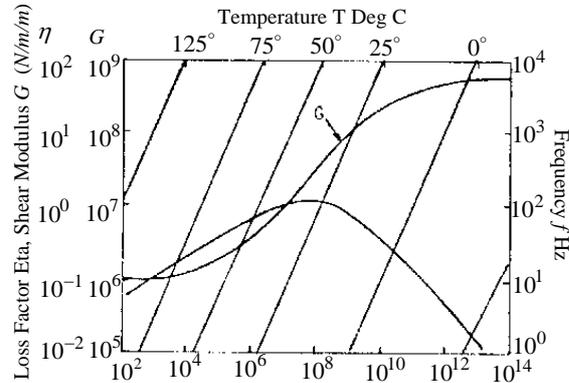


Figure 3. Damping and Stiffness Properties for SMRD 100F90⁹

To use this figure find the frequency of interest on the right vertical coordinate. A horizontal line through this frequency will cross the oblique line which represents the temperature of interest. A vertical line through this crossing point will intersect the G and η curves and give these two properties at the frequency and temperature. The values shown on the bottom coordinate are known as reduced frequencies and were used to create the figure. It can be seen that the modulus of the viscoelastic materials increases with frequency and decreases with temperature. The loss factor increases initially and then decreases.

3.2 Estimating Energy Dissipated in Viscoelastic Material

The values in Table 2 were obtained from Figure 3 at temperature 25° and have been used in the following analyses.

Table 2. Stiffness and Damping Properties of SMRD 100F90 at 25°

Frequency (Hz)	Storage Modulus (N/m^2)	Damping Modulus (N/m^2)	Loss Factor
1	4.15E6	2.83E6	0.683
1.778	5.09E6	4.17E6	0.820
3.162	6.72E6	5.97E6	0.888
5.623	8.20E6	7.57E6	0.924
10	1.0E7	1.0E7	1.0
17.78	1.37E7	1.49E7	1.08
31.62	1.89E7	2.13E7	1.13
56.23	2.59E7	2.92E7	1.13
100	3.34E7	3.62E7	1.08

Let F be transverse force acting on a thin element of viscoelastic material with shear area of A and thickness of h as shown in Figure 4.

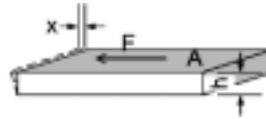


Figure 4. Simple Model of Viscoelastic Material

According to the simple relationship between stress and strain, it can be shown that

$$\frac{F}{A} = (1 + i\eta)G \frac{x}{h} \quad (4)$$

The relationship between harmonic force F and the displacement x can be found and the area in the loop they form (which gives the energy dissipated) can be calculated:

$$E = \pi F_0 x_0 \sin \theta = \frac{\pi F_0^2 h \eta}{l w G (1 + \eta^2)} \quad (5)$$

Where F_0 is the force amplitude; x_0 is the displacement amplitude and θ is the phase angle between the force and the displacement.

3.3 Detailed Bolted Joint Model with Viscoelastic Layer

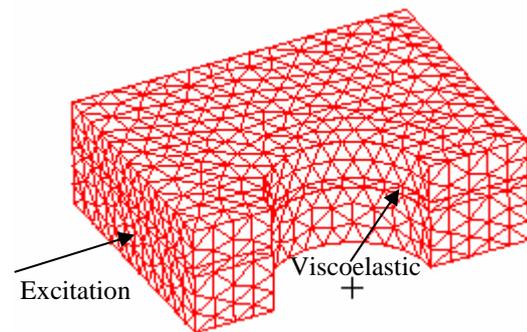


Figure 5. Detailed Bolted Joint with Viscoelastic Layer

Part of a detailed bolted joint with a viscoelastic layer is shown in Figure 5. The effective shear carrying area of the viscoelastic layer in a whole joint is $25mm \times 16mm - \pi \times 3mm \times 3mm$. The thickness of the layer is 0.5 mm . Ten node tetrahedral solid elements were used in the model. Due to the symmetry, only a quarter of the joint was modelled.

FE frequency response analyses were carried out at different forces. Details from one analysis are given below:

At 1 Hz and with an excitation force of $1000N$

$$x_0 = 0.534304mm$$

$$\theta = -33.7^\circ$$

$$E = \pi F_0 x_0 \sin(33.7^\circ) = 1.863J$$

From the estimation formula (equations 4) it can be shown that

$$x = \frac{Fh}{A(1+i\eta)G} \quad (6)$$

Assume $F=1000N*2$, $h=0.5mm$, $G=4148694\text{ N/m}^2$, $\eta = 0.683$, $A=16*25-\pi*3*3=371.7\text{ mm}^2$, substitute into (6), then

$$x_0 = 0.00053550m$$

$$\theta = -34.333^\circ$$

$$E = \pi F x_0 \sin \theta = 1.898J$$

The results from these two models were compared. It was found that the displacement error in the estimation formula was 0.22%; the phase angle error was 1.9% and the error of energy dissipated was 1.9%. It can be seen that using estimation formula in the preliminary analyses was quite reasonable.

3.4 Analytical Models of Bolted Joints with Viscoelastic Layer

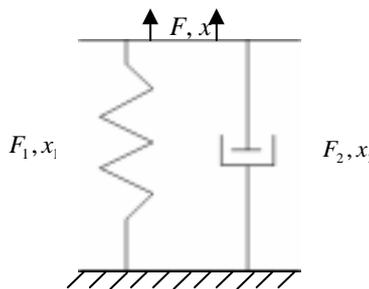


Figure 6. Kelvin or Voigt Model

Maxwell Model (a spring and a dashpot in series) and Kelvin or Voigt Model (a spring and a dashpot in parallel) are two models people used often to represent the viscoelastic material. The Kelvin model shown in Figure 6 was used to derive the formula here. The similar process can be used on Maxwell model. The motion equation of the Kelvin model is:

$$F = F_1 + F_2$$

$$x = x_1 = x_2 \quad (7)$$

$$F_1 = kx_1$$

$$F_2 = c\dot{x}_2$$

Assuming $F = F_0 \cos \omega t$ and solving the equation $F = kx + c\dot{x}$, gives (the steady-state):

$$x = \frac{F_0}{\sqrt{k^2 + c^2 \omega^2}} \cos(\omega t + \phi) \quad (8)$$

where

$$\tan \phi = \frac{-\omega c}{k} \quad (9)$$

It can be seen that

$$x_0 = \frac{F_0}{\sqrt{k^2 + c^2 \omega^2}} \quad (10)$$

From above equations, it can be shown that:

$$k = \frac{F_0}{x_0} \cos \phi$$

$$c = -\frac{F_0}{\omega x_0} \sin \phi \quad (11)$$

Using the estimation formula (equation 4) k and c can be found as:

$$k = \frac{AG}{h}$$

$$c = \frac{AG\eta}{h\omega} \quad (12)$$

3.5 Including Bolted Joints with a Viscoelastic Layer in a Simple Satellite Model

3.5.1 Satellite model and properties of spring dashpot joints

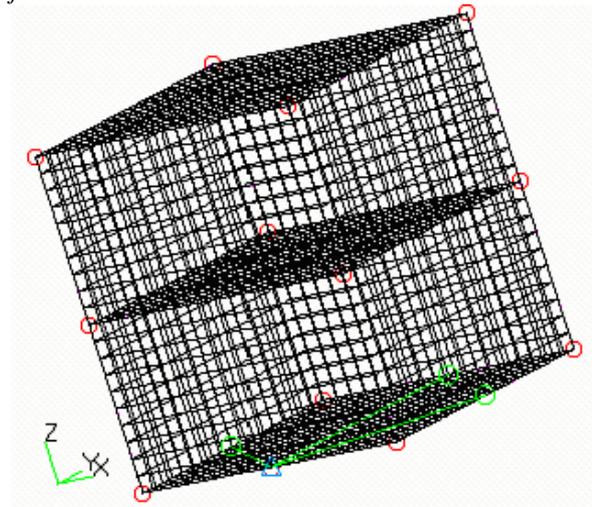


Figure 7. Simple Satellite Model

The simple satellite model used is shown in Figure 7. Bolted joints were assumed to lie on the four vertical edges. The Kelvin model was used to model the joints with their viscoelastic layers. Each pair of coincident

nodes on the vertical edges was connected by three springs and three dashpots. They transmitted loads in the x, y and z directions separately.

G and η for the viscoelastic material as given in Table 2 were used in equation (12). The thickness of the viscoelastic layer was assumed to be 0.1 mm.

As the length of the satellite edge was 1 m and there were 21 bolts on each edge and the assumed width of the joint was 0.01 m and the bolt hole diameter was 0.005 m, the area for the viscoelastic layer in one joint can be found as:

$$A = 1 \times 0.01 \div 21 - \pi \times 2.5^2 \times 10^{-6} = 4.565 \times 10^{-4} m^2$$

The parameters of the spring dashpot are shown in Table 3. The joint in z direction behaves like two joints in x or y direction in series, so the stiffness and the damping coefficient in z direction are only half of those in x and y directions.

Table 3. Properties of Spring-Dashpot Systems

f (Hz)	Kx, Ky (N/m)	Cx, Cy (N.s/m)	Kz (N/m)	Cz (N.s/m)
1	1.89E7	2.06E6	9.47E6	1.03E6
1.778	2.32E7	1.71E6	1.16E7	8.53E5
3.162	3.07E7	1.37E6	1.53E7	6.86E5
5.623	3.74E7	9.79E5	1.87E7	4.89E5
10	4.56E7	7.26E5	2.28E7	3.63E5
17.78	6.27E7	6.08E5	3.13E7	3.04E5
31.62	8.62E7	4.88E5	4.31E7	2.44E5
56.55	1.18E8	3.76E5	5.92E7	1.88E5
100	1.52E8	2.63E5	7.63E7	1.31E5

Two different satellite models were created to make some comparison. The one (shown in Figure 7) in which the joints with viscoelastic layer were modelled by spring-dashpots was called ViscoSat. Another one in which the FE nodes where the joints lie were connected directly by MPC was called MPCSat. The energy input to the satellite was also calculated from the bottom separation springs.

3.5.2 Modelling and results

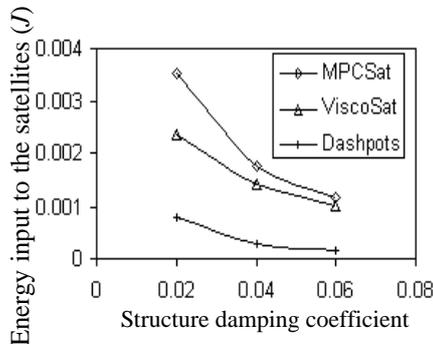


Figure 8. Input Energy Changing with Structural Damping Coefficient in Different Satellite Models

Figure 8 shows the variation of energy input to the satellite models with structural damping coefficients. The excitation acceleration is $0.1 m/s^2$ in y direction. All the values were obtained at the first natural frequency of different models. It can be seen that the viscoelastic layer decreased the energy input to the satellite significantly. The curve marked “Dashpots” gives the energy dissipated by dashpots only. The energy dissipated by the dashpots was compared with the energy input to the ViscoSat and shown in table 4. It can be seen that viscoelastic layer dissipated a significant part of the input energy.

Table 4. the Percentage of Energy Dissipated in the Viscoelastic Layer to the Input Energy

Structural Damping Coefficient	0.02	0.04	0.06
Energy Percentage	34%	20%	14%

Figure 9 shows how the maximum displacement of satellite models changes with the structural damping coefficients. It can be seen that the viscoelastic layer decreased the maximum response of the satellite model significantly.

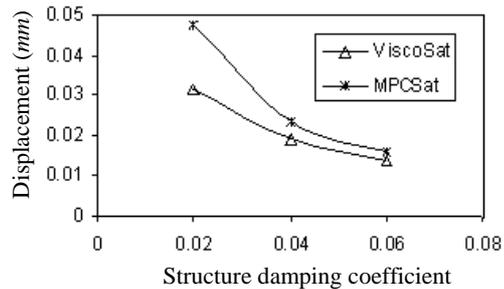


Figure 9. Variation of the Maximum Displacement with Structural Damping Coefficient for Different Satellite Models

4. NONLINEAR MODEL OF VISCOELASTIC LAYER

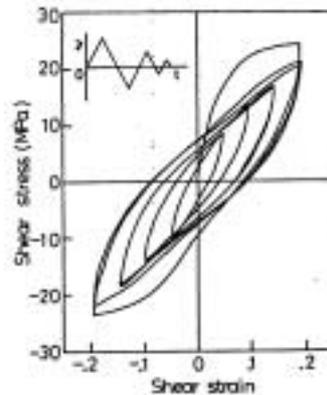


Figure 10. the Stress Strain Hysteresis Loops¹¹

The hysteresis loop of a spring dashpot system is an ellipse, but the loops of a real viscoelastic layer are

not, as shown in Figure 10. In order to obtain some experimental data for further research, some experiments were carried out.

4.1 Experimental Work

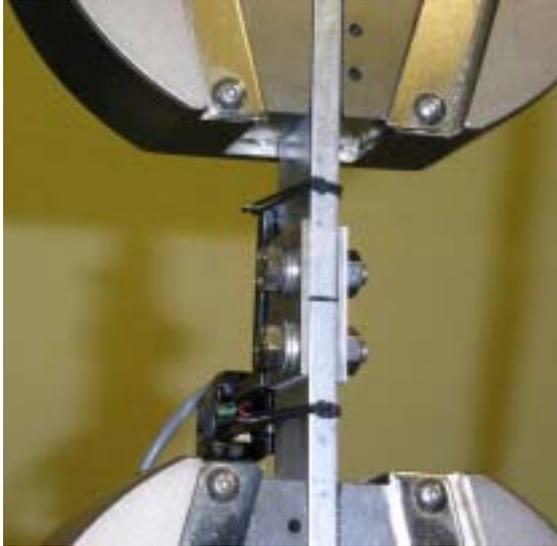


Figure 11. Specimen with Extensometer Set-up in The Machine

The joints used in this experiment were lap joints composed of two 25x80x6mm aluminium bars with two 25x34x2mm aluminium clamping plates as shown in Figure 11. A thin layer of viscoelastic material was put between the clamping plates and the clamped bars. An extensometer was used to measure the relative movement of the joints. There is a large clearance between the holes and the bolts so that the viscoelastic layer can develop a significant strain: the hole having a diameter of 8mm and the bolts a diameter of 6mm.



Figure 12. A film of Cho-Therm T500

There are a lot of viscoelastic materials which can be chosen as damping layers. For use in a real satellite

the properties which should be considered not only include those mechanical ones like strength, stiffness and damping but also those making it suitable for space use, like out-gassing and thermal properties etc. In this preliminary experimentation these parameters were not considered. The aims of the experiment were to measure typical viscoelastic material properties and to obtain the data for validating the numerical models.

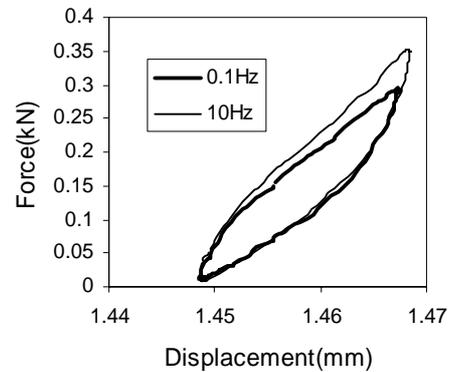


Figure 13. Hysteresis Loops of a Bolted Joint with Cho-Therm T500

A thermal interface material named Cho-Therm, which contained a silicon binder with a boron nitride filler, was chosen for initial testing. It looks like a piece of thick paper (Figure 12) and can be cut into the shape required. This material has been used in a prototype satellite as gaskets to promote heat transfer, but not in all the bolted joints. Figure 13 shows two typical hysteresis loops from the tests. One test was carried out at 0.1Hz, another at 10Hz. Obviously the frequency affected the behaviour of the material and the layer absorbed energy. However Cho-Therm has a small elongation, normally below 10%, and at this elongation it cannot transfer much force. This limits the energy absorbing capacity of the material. It also has too narrow a range of material behaviour, so limiting our interest in researching it as a damping material.

Another material selected is a silicone rubber named Versasil from Nusil company. It has an elongation of 875% and a stress of 1.86 MPa at a strain of 100%. It still cannot sustain much force, but can be used to investigate the viscoelastic behaviour and validate the non-linear spring dashpot model to be used.

Before curing, the rubber is very flexible. It was rolled into a thin sheet and then cured in the oven at 100 °C for about 1.5 hours. Following this it is like a normal rubber and can be cut into the shape required and put into the joints (see Figure 14).

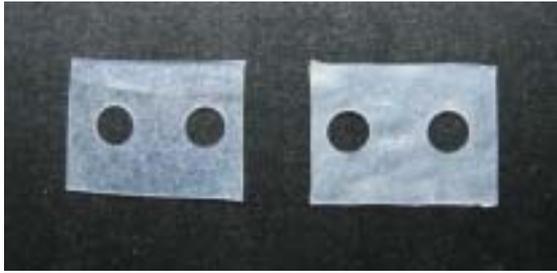


Figure 14. Versasil Used in the Bolted Joints

Versasil film of thickness of about 0.8mm was used for the cyclic tests. Different frequencies and different displacement amplitudes were applied.

Figure 15 shows two hysteresis loops. One is at 1 Hz, another one is at 10Hz. The amplitude of the displacement is 0.1mm. The stiffness of the rubber does increase with frequency as indicated in the literature.

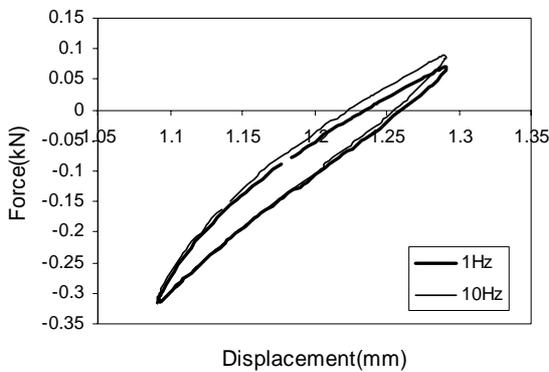


Figure 15 - Hysteresis Loops of a Bolted Joint with Versasil 50 at 1 Hz and 10 Hz

Figure 16 shows the results of tests when the displacements of joints are 0.1 mm and 0.3 mm separately. The frequency is 10Hz.

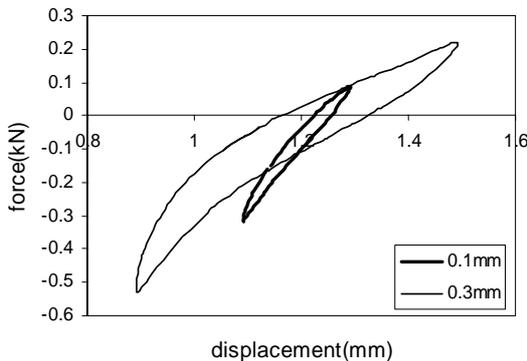


Figure 16. Hysteresis Loops of a Bolted Joint with Versasil 50 at Different Amplitudes of Displacement

From Figure 15 and 16, the dependence of properties on both frequency and excitation amplitude can be observed. It is dominated by the strain amplitude

effects. It seems that at higher strain rates, the Versasil is more compliant.

4.2 Fitting the Curves

Different spring and dashpot parameters for the Kelvin model were used to assess the effect on the hysteresis loop shape. The spring force-displacement relationship is assumed to be $F = a\Delta^b = k(\Delta)\Delta$. The damping coefficient of the dashpot is c . Different parameters (as shown in Table 5) for the system were used. The results are shown in Figure 17. The frequency of the excitation force is 10Hz.

Table 5. Parameters for Different Spring-Dashpot Systems, (a) for Figure 17a, (b) for Figure 17b

(a)			
	curve 1	curve 2	curve 3
Excitation Force	100	300	500
a	10000		
b	3		
c	10		

(b)			
	curve 1	curve 2	curve 3
Excitation Force	1000	3000	5000
a	10000		
b	0.6		
c	100		

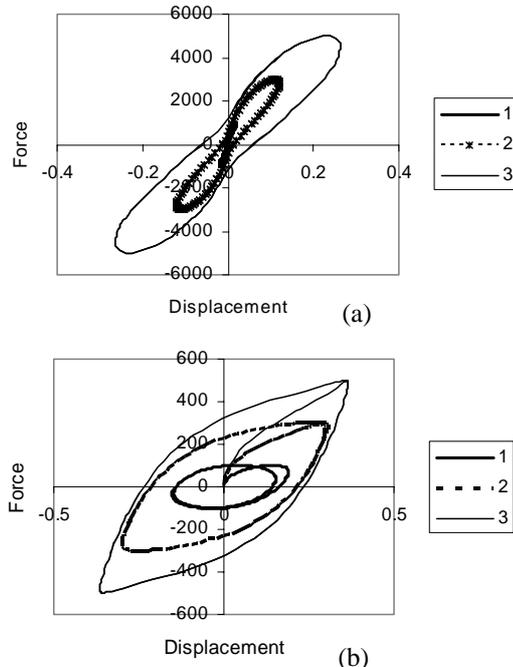


Figure 17. Force Displacement Loops for Spring-Dashpot Systems

It can be seen from figure 17 that various loop shapes can be obtained from the non-linear spring dashpot system. If a proper form of non-linear spring is chosen, it might be possible to replicate the loop seen in the experiments. By observing the experimental loops one can see that at the both ends of the loops the stiffness is bigger and in the middle the stiffness is smaller. A stiffness of the form $k = a_1 \times \Delta^2 + a_2 \times \Delta + a_3$ was used to fit the curve.

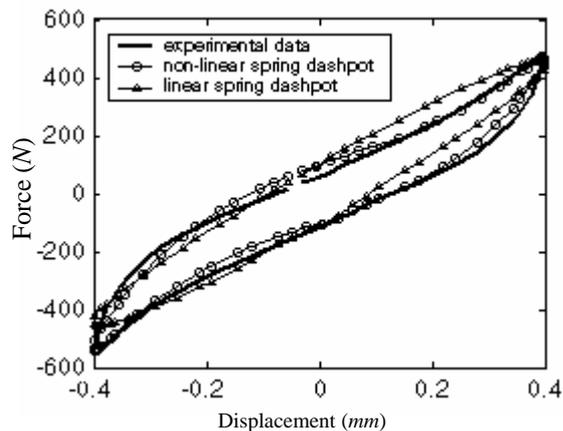


Figure 18 – Comparison of Experimental Data and Data From the Optimised Spring Dashpot System for Versasil

One of the experimental results was selected and used to find the corresponding stiffness of the spring so that the loops from both systems match as closely as possible. The optimisation function in Matlab was used to find the best coefficients a_1, a_2, a_3 and the best damping coefficient c . A linear spring dashpot system was also used and the stiffness of the spring and the damping coefficient of the damper were also found by using the optimisation process. The results are shown in Figure 18. It can be seen that the curve from the non-linear spring dashpot system is closer to the experimental data than the linear system is. A better fit may be found if some other forms of stiffness function or even damping function are tried.

5. CONCLUSIONS

From the research, several conclusions can be obtained:

- Plain bolted joints working in micro-slip stage dissipate only a small percentage of the energy input to the structure
- Spring dashpot models can give an approximate and simple evaluation of the damping property of a bolted joint with a viscoelastic layer in a large structure.
- Non-linear spring dashpot systems can be used to improve the modelling of the joints with viscoelastic materials in a large structure.

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