Characteristics of a bolted joint with a shape memory alloy stud

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Abstract

Creep is an important factor that contributes to the load loss and tightness failure of bolted joints. Retightening of the joint can be expensive, time consuming and therefore is an undesirable solution. Currently most efforts are focussed on reducing load losses directly by tightening to yield, improving material creep properties or making joints less rigid. An alternative solution of current interest is the use of bolts in shape memory alloy (SMAs). However, very few experimental studies are available that demonstrate its feasibility. The objective of this study is to exploit the benefit of the shape memory and superelasticity behaviors of a SMA stud to recover the load losses due to creep and thermal exposure of a gasket in a bolted joint assembly. This paper explores several avenues to investigate and model the thermo-mechanical properties of a bolted joint with a Nickel-Titanium SMA stud. A stiffness-based analytical model which incorporates the Likhachev model of SMA is used as a representation of an experimental bolted joint assembly. Using this model the rigidity of the experimental setup is optimized to make the best use of the SMA properties of the stud. This theoretical model is validated by a Finite Element (FE) Model using a custom FE material model which also implements the SMA material model. Finally an experimental test bench with an optimized stiffness derived from analytical simulations is used, with and without gaskets to demonstrate the ability of the SMA stud to recover load losses.
Keywords: shape memory alloys, bolted joints, creep, superelasticity, SMA.

1 Introduction

Load losses due to creep in any bolted joint can be problematic, even small creep losses of 0.1mm, can cause a total loss of bolt load. Several methods are in use to

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attempt to reduce these losses, including tightening to yield, using gasket materials or designs that reduce creep losses, or using less rigid joints. Some research has been done in the use of Shape-Memory-Alloys in a bolted joint in different ways. Peairs et al. [1], conducted research in using a thick SMA washer in a bolted assembly based on a piezo crystal to qualify the load in the joint. When a load loss is detected in the joint a heating element would activate the SMA washer. They demonstrated that load recovery was possible, however due to the nature of piezoelectric crystals the actual load in the joint and the percentage load gained was not determined. Antonios et al. [2] as well as Hesse et al. [3] tested a thick SMA washer with a load cell. Based on the same concept of heating the element when a load loss was detected they succeeded in recovering the load using the SMA washer. Labrecque et al. [4] used a Belleville washer to recover load loss in a bolted joint, by electrically heating the washer when the load was lost. The heating activated the washer, and generated additional load, however after the cooling stage it was found that significant if not all the total load was lost depending on the operating conditions. Ma et al. [5, 6] simulated the use of a bolted joint assembly to absorb seismic energy in structural joints. The simulation was conducted primarily by FEM and demonstrated the ability of SMA bolts to absorb significant stains and return to their initial state, however no experimental work using SMA bolts was conducted. Overall, the concept of using SMA in a bolted assembly has undergone some experimental and theoretical research, however most of the experimental work focuses on directly creating load losses by loosening the bolt, and not by imposing creep losses. Furthermore the bulk of the experimental work was conducted on SMA washers; however for the application of SMA bolts in bolted joint assemblies, little experimental work is available in the literature.

This paper investigates the use of a Ni-Ti SMA stud in a bolted joint assembly to recover creep losses. The research will focus on using the combined effects of Shape Memory and Super-Elasticity (see Fig. 1) in order to recapture load losses due to creep. First an analytical model is developed permitting a quick evaluation of the behavior of SMA in a bolted joint. A finite element model is also developed to demonstrate the ability of FEA to tackle more complex joints such as with multiple bolts in SMA. These models incorporate the Likhachev model of SMA [7], incorporated into MATLAB and ANSYS through a user subroutine by Therriault et al. [8]. The models are then validated against an experimental study of the use of a SMA bolt in a bolted gasketed joint.

2 Analytical model

In order to make best use of the shape-memory and super-elasticity effects of the nickel-titanium stud in the experimental test apparatus, a simplified analytical model was implemented.

The model consists of 4 elements: The SMA stud, a spring element to represent the stiffness of the test rig, a rigid element which is used to simulate the thermal expansion of the flange, and a creep element to simulate the properties of the gasket.

$$D = F_{SMA} * k_{Assy} + \Delta D_{Gasket} + \alpha L_{Clamped}\Delta T, \qquad k_{Assy} = \frac{1}{\frac{1}{k_{bell}} + \frac{1}{k_{steel}}}$$

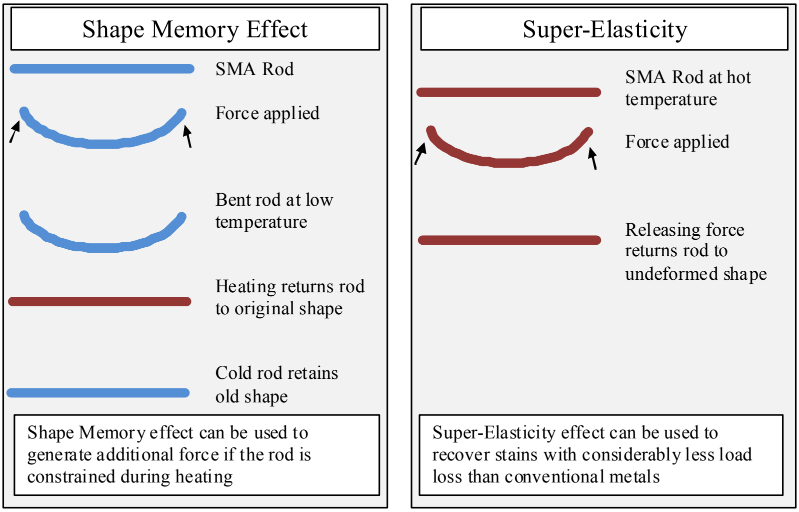

Figure 1: Schematic representation of shape memory and super-elasticity.

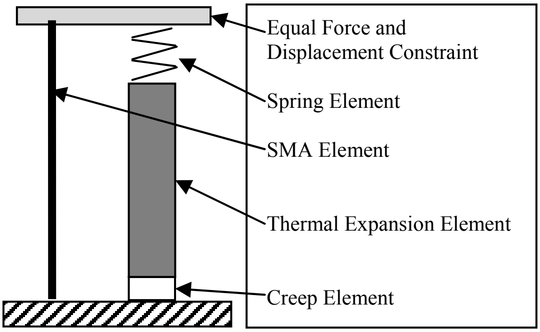

Figure 2: Analytical model.

The displacement obtained, along with the temperature is forwarded to the SMA element, which yields a new force F_{SMA}. This is converged iteratively for each temperature or displacement change resulting in a 1D simulation of the behaviour of the experimental rig.

The Likhachev micromechanical model of SMA, implemented into a numerical MATLAB [11] subroutine [8], was used in order to represent the thermo-mechanical behaviour of the SMA Stud. The stiffness element, which in the experiment consists of Belleville washers, is used to simulate the desired flange assembly joint rigidity. The rigid element uses the thermal expansion coefficient of steel and the clamped length of the modelled flange to determine thermal strains of the model. Finally the creep element can use either a logarithmic thermal creep law, experimental curve fits of creep data, or simply consider a creep displacement linearly. Whereas the linear model does not give an accurate time representation of creep over time, it gives accurate stresses and strains before and after creep losses if the creep displacement is known.

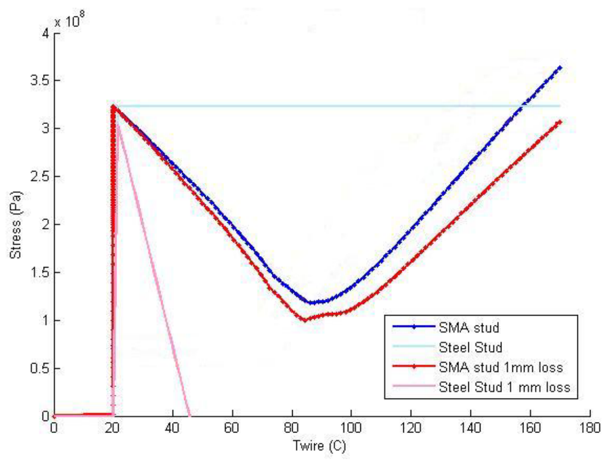

Figure 3: Effect of creep on SMA and steel bolt.

As shown in Fig. 2, there is considerable loss in bolt load during the heating phase, before the austenitic transformation temperature. This is primarily caused by the properties of the shape memory alloy stud. These properties can vary considerably based on the heat treatment given and the nickel titanium ratios [9].

Using the linear creep model, a gasket creep displacement of 1 mm was introduced during heating in a joint having an SMA bolt and compared to a joint with a B7 steel bolt. It is clear that for large creep such as those expressed with PTFE gaskets in industrial flanges, the SMA stud retains much higher loads than the steel bolt.

3 Numerical FE model

The axisymmetric arrangement of the simulated flange with an SMA stud in the center lends itself well to a 1 dimensional analysis which can be treated analytically without great difficulties. However in order to model more complex flanges and configurations with multiple bolts, and various non symmetric thermo-mechanical loading, requires a more detailed model. In order to accomplish this modeling, a numerical FEM model was developed using ANSYS workbench [10].

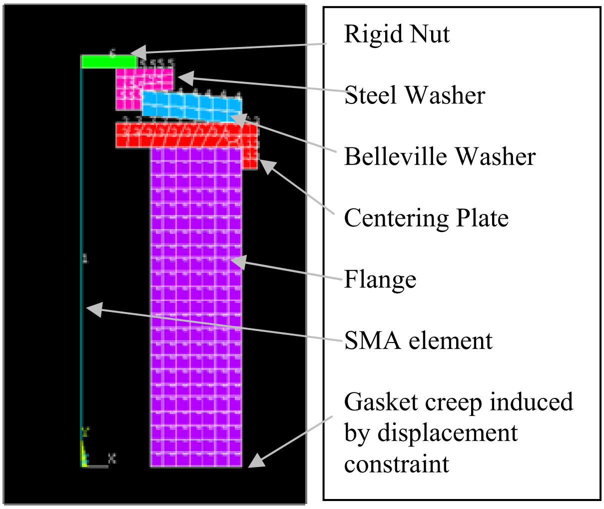

Figure 4: FE model of the experimental assembly.

The modeling of the shape memory behavior is accomplished using a user subroutine material model that is incorporated to ANSYS [8]. This can adequately represent the tension loads in a bolt. The advantage of using an FEM model is that multiple SMA and non SMA bolts can be used in various configurations to design and optimize a complex structure such as a bolted flange which utilizes SMA to recapture creep losses.

Since the contact stresses between the metal elements do not greatly influence the properties of the assembly, they were modeled using point constraints. This results in a model of the experimental assembly which has a constant stiffness. This model is then used to validate the analytical model, with excellent results as the stiffness's used are the same as shown in Fig. 5.

4 Experimental setup

The experimental test rig allows a gasket to be placed between two hollow cylinders with a B7 steel bolt or an SMA bolt in the center. A cartridge heater is placed around the assembly and the exposed surfaces are insulated to maintain an even temperature distribution. The top flange is instrumented with a full strain gauge bridge, calibrated to measure axial load. The SMA bolt is instrumented with thermocouples and strain gauges, to ensure even temperature distribution and measure the strain. Thermocouples are also used to measure air temperature to control the heater and the temperature of the bolt.

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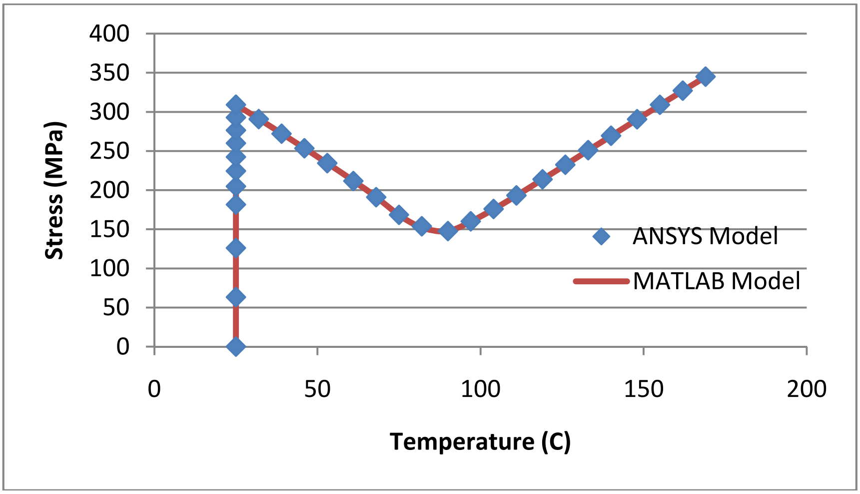

Figure 5: Comparison of the analytical model and FEM variation of load with temperature of the SMA bolt.

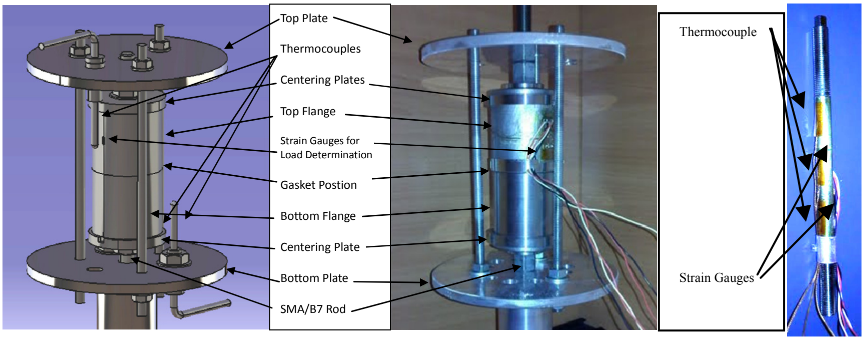

Figure 6: Experimental SMA bolt assembly.

5 Results and discussion

The experimental results are conducted in two stages. A small scale test using wire samples of the SMA rod (from which the stud is machined) were conducted by straining the samples to various strain levels, then heating them while restraining the displacement, and measuring the force generated.

With this characterization available for small scale tests the Analytical and Finite Element models can be supplied with the necessary information they require to model the behavior of this specific sample of Ni-Ti alloy.

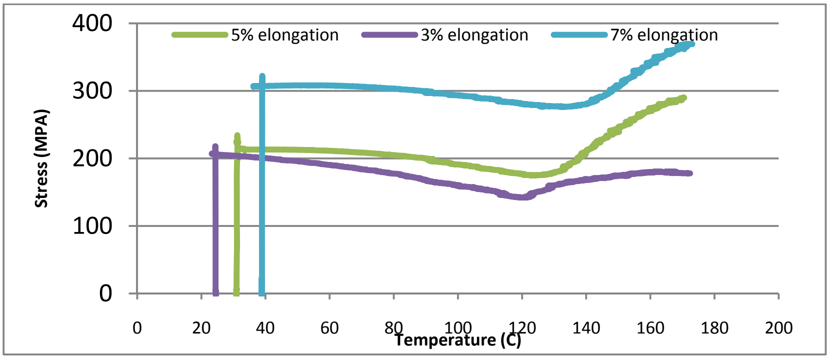

Figure 7: Small scale characterization of SMA alloy.

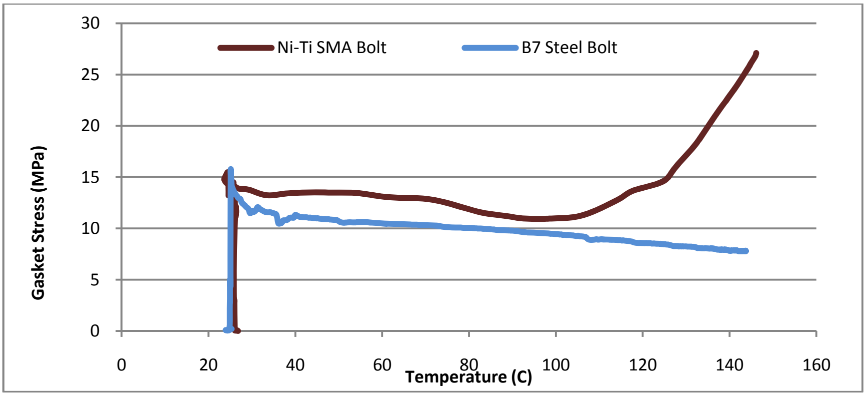

Figure 8: Comparison of the behavior of a B7 and an SMA stud in an experimental bolted gasketed joint.

A 3/8” B7 Steel stud is compared to a SMA stud both loaded to a gasket stress of 15MPa (2.1ksi) with a 1/8” expanded PTFE gasket. Both are then heated to 150°C (300°F) and allowed to creep for one hour. The results are compared and visibly demonstrate the advantages of an SMA bolt.

The gasket thicknesses were measured post test, and the SMA bolted joint creeped 40% more than the B7 joint, likely due to the increased load. This further shows the advantages of SMA since even with the additional creep, the SMA bolt still generated a considerable amount of load, whereas the steel bolt lost a considerable amount of load.

Comparing small scale test and experimental test rig results with Likachev model results yields a good correlation between all 3. The experimental rig results seem to generate higher loads than predicted. This is due to the residual stresses generated by cutting the smaller wire samples from the rod, which has a detrimental effect on their properties.

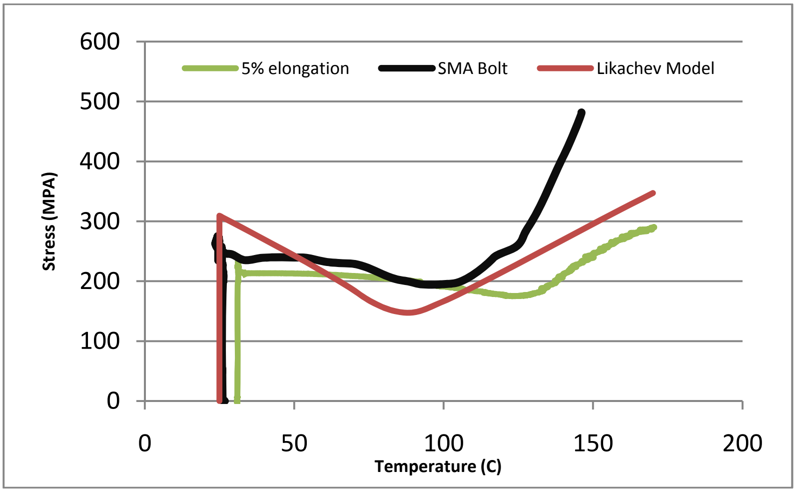

Figure 9: Comparison of small scale, experimental and numerical results.

6 Conclusion

In conclusion, preliminary results are promising and the use of a SMA rod has considerably reduced the load loss due to creep in the gasket. It was also demonstrated that additional load can be generated to further compensate creep losses at higher temperatures. The application of the Likachev model of SMA in both the analytical and FEM models yields good congruence with experimental results.

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