Chapter 5
Experimental and Numerical Characterization of Relaxation in Bolted Composite Joints

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Abstract This paper reports on experimental and numerical studies of the effects of bolt preloads, viscoelasticity, and external applied static and dynamic loads on bolt load relaxation in a unidirectional carbon/epoxy composite bolted joint. Experimental measurements of bolt-connected joints in three-point bending specimens were employed in the studies, and relaxation was observed to depend on the initial preload and external dynamic applied loads. It was observed that for any magnitude of external load the bolt load relaxation decreases with increasing initial preload. These findings emphasize the importance of the magnitude of the preload. It was concluded that only about 1/3 of the bolt force relaxation in the composite joints could be attributed to viscoelastic behavior of the polymer matrix in the composite, and the remaining 2/3 of the relaxation is likely caused by other mechanisms such as bolt thread slip, plasticity and/or external excitation. This paper also briefly reviews some relevant relaxation studies found in the literature for mechanically fastened composite and hybrid joints, as well as the effects of environmental conditions such as temperature and moisture on joint relaxation, and points out some gaps where more research needs to be carried out to understand the behavior of such joints.

Keywords Composites • Bolted joints • Viscoelastic • Relaxation

5.1 Introduction

In today's economy, aircraft and automotive vehicle manufacturers are scrambling to improve fuel efficiency by improving the engine technology and/or reducing weight by using light weight composite materials, which have high strength-to-weight ratio. Commercial airliner and business jet makers such as Boeing, Airbus and Gulfstream Aerospace Corporation are making greater use of composite materials in their airframes and primary structures than ever before. Advanced composites on the Boeing 787 account for 50% of its structural weight mainly in the wings and fuselage [1]. Gulfstream Aerospace makes modest use of composite materials on its new and innovative business jet G650 from tail assembly to floor panels and furnishings [2]. The usage of composite materials as primary structures in aircrafts presents challenges in terms of manufacturing and joining the parts. In composite structures, three types of joints are commonly used, namely, mechanically fastened joints, adhesively bonded joints, and hybrid combinations of mechanical and bonded joints. Combinations of bonded and mechanically fastened joints are primarily used in the aerospace industry to join two or more composite parts, or to join a composite part to a metallic structure (hybrid joint). Mechanically fastened joints usually consist of either solid bolts with collars or nuts, rivets, screws and blind bolts (pull-type). Some common advantages of fastened joints are: simple joint configuration, and ease of assembly, manufacturing and inspection. But when joining composite structures one has to consider stress concentration, poor bearing strength of composites, joint fatigue and environmental exposure. Any joint in a composite structure, if not designed properly, may act as damage initiation point and may lead to failure of the component at that location. For fiber-reinforced composites joined mechanically through bolts with an initial through-the-thickness

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preload, viscoelastic relaxation has a direct bearing on how much of the initial preload will be retained in the joint over time, and how much the preload will be affected by external mechanical loads and environmental conditions. The question becomes hard to answer when the composite material is fastened to metallic structures to form hybrid joints.

The procedure for designing mechanically fastened composite or hybrid joints relies mostly on experimental data. An overview of design requirements, different approaches, and industrial codes of practice used for the design and analysis of bolted and bonded joints is given by Broughton, et al. [3]. In the most recent review on mechanics of mechanically fastened joints in polymer composite structures [4], standard methods available to determine joint design allowables such as bearing strength, open hole tension (OHT), open hole compression (OHC), filled hole tension (FHT) filled hole compression (FHC), and bearing by-pass are given. The article also discusses the effects of geometric parameters (width-to-diameter (w/d), edge distance-to-diameter (e/d), washer size, and bolt type), hygrothermal effects, and bolt clamp-up and relaxation (or preload) on bearing strength, failure load and fatigue life in composite joints.

In both of the above articles [3, 4], it is stressed that for composite laminates, the through-the-thickness (TTT) force (preload) exerted by the fastener on the joined members is critical to the performance of the joint. Bolt preload induces compressive load in the washer and material being joined, and tensile load in the bolt shank. This serves two purposes: in terms of carrying load by friction and suppressing delamination driven failure modes, while increasing bearing strength. However, for composite structures, if the preload is not sufficient to begin with, some of the preload may be lost in the joint due to viscoelastic behavior. It is well known that for polymeric composites, viscoelastic effects are predominant in the matrix dominated TTT direction, and this viscoelastic behavior is magnified when the composite is exposed to elevated moisture and/or temperature levels. The relevant previous studies found in the literature on clamp-up force relaxation in composite-to-composite joints and composite-to-metal or hybrid joints, are reviewed in the next two subsections.

5.1.1   Composite-to-Composite Joints

As mentioned earlier, it is important to select an optimum preload for the joint or torque applied to the fastener. Some designers use the existing MSFC-STD-486B design code as a guideline from NASA Marshall Space Flight Center (MSFC) [5–7], which was developed originally for metallic structures. A process has been developed for recommending the torque range to apply for fasteners as per MSFC-STD-486B to join composite structures [8]. This process calls for the use of a torque versus tension test, and monitoring of the joints using acoustic emission during the test. It is also recommended that nondestructive thermal images and thermographs be taken after the tests. Some studies also recommend using instrumented bolts to measure the pre-load in composite joints while applying torque to the fastener [9]. Earlier experiments in 1980s showed the clamp-up force relaxation in graphite/epoxy (T300/5208) laminates [10, 11], under three steady state environments: room temperature ambient (RTA) with 0.46% moisture content by weight, room temperature dry (RTD), and elevated temperature (66°C) dry (ETD). Relaxation in clamp-up force of 12% for RTD and 14% for RTA for a 100 day period was reported for a double-lap joint configuration tightened with an initial torque of 5.65 N-m, which clearly indicates that increasing moisture content increases the relaxation.

Fastener type, different torque values and also the material may have different effects on bolt load relaxation. Horn and Schmitt [12, 13] showed that bolt load relaxation for graphite/thermoplastic composite materials (Dupont's IM6/KII) is 3.8% more than that of the ICI-Fiberite's IM8/APC(HTA) in a single-lap shear configuration for a 1,000 h period, with initial torques of 65 and 100 in-lbs. It was also found that the relaxation rate increased by 4.7% for hot (250°F)/dry (0.0% moisture) conditions. To understand the effect of bolt-load relaxation on the bearing strength, the composite specimens were tested to failure after the end of 1,000 h relaxation tests. On comparing the bearing strength of relaxed joints with those of joints tested to failure immediately after tightening, it was concluded that the bolt-load relaxation did not significantly affect the bearing strength. Zhao and Gibson [14] showed that compressive clamping stress relaxed by 18% and 15% in E-glass/epoxy beams with and without polymeric interleaves, respectively, for a period of 50 h, whereas the corresponding relaxation in an aluminum beam was negligible.

It is clear from the previous experiments that exposure to high temperature and moisture increases the clamp-up force relaxation in composite joints. But the effect of hygrothermal cycling on clamp-up force relaxation is unclear as observed by Chen [15, 16]. Experiments on IM6/3501-6 $[45/90/-45/0_3/\pm45/0_3/\pm45]$s showed a 5.5% and 7.6% reduction in clamp-up force over a period of 4 months at RTA and 98°F/98% Room humidity (RH) 12 h on-off cycling, respectively, but at 120°F/98% RH cycling the results showed an increase in the clamp-up force by about 55%. For IM7/8552 $[45/0]_{10}$,21.7% reduction in clamp-up force was observed at RTA, whereas there was no change in the clamp-up force at 120°F/98% RH cycling. It was concluded that material swelling under humid room conditions and some possible nonlinearity of the instrumented bolt characteristics were responsible for this increase.
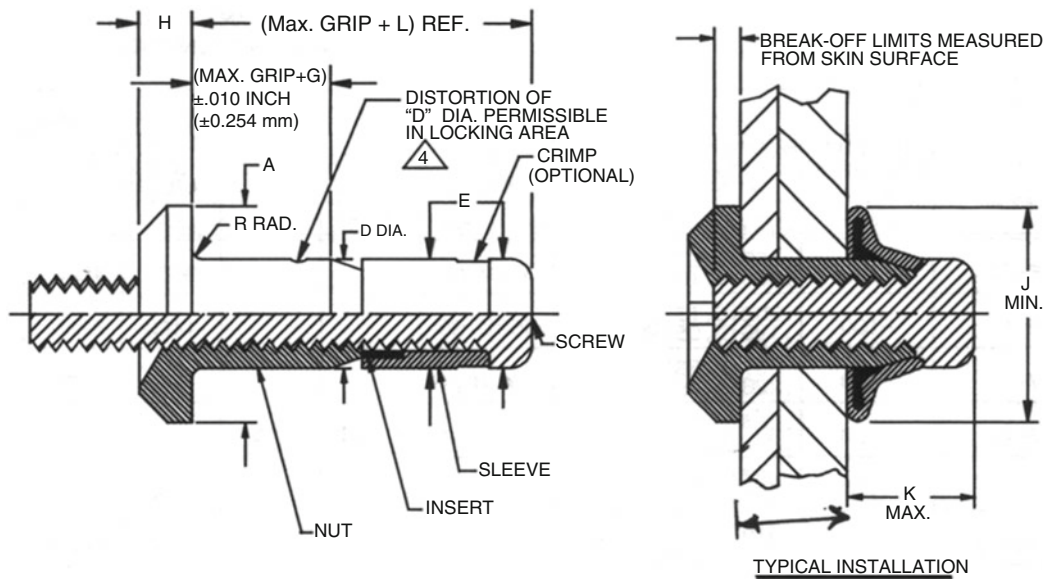
Fig. 5.1 Blind Fastener protruding head MBF 2010 [18]

It is suggested that titanium alloy fasteners be used to prevent galvanic corrosion and tension heads be used to avoid pull-through for composite assemblies in aircraft primary structures [17]. It is very common practice to use blind or one-sided fasteners in primary structures where access to both sides of the assembly is not possible or practical (e.g., general aviation wing covers, empennage surfaces, and control surfaces). Monogram Aerospace Fastener is one of the leaders in blind bolt technology, its patented Composi-Lok® is approved for use on most of the composite airframe programs [18]. A typical blind fastener joint is shown in Fig. 5.1. The blind fastener consists of a stem and a sleeve which forms the fastener head. The stem extends through the sleeve head in the form of a threaded shank. The other end of the stem has a diameter slightly larger than the sleeve. The sleeve rests against the part being fastened and the stem is pulled out, flaring the sleeve and thus forming the bulb which serves as a nut. The quality of the joint, the clamp-up force and the strength of the joint have been shown to depend on the ratio of the part thickness to the manufacturer specified grip length ratios (part thickness to recommended grip length) [19]. Clamp-up force relaxation in graphite/epoxy ([±45/0]s) composite laminate joints using blind fasteners (NAS1919-M06) has been investigated experimentally [20]. The clamp-up force was measured for different ratios of part thickness to recommended grip length. For a 21 day monitoring period, the relaxation was observed to be 3–8%, and it was also found that the rate of relaxation increased with increasing grip ratio.

5.1.2 Hybrid Joints

It is very difficult to avoid composite-to-metal connections in aircraft structures, and the design of these connections presents its own challenges as additional loads are generated due to thermal expansion differences, and the behavior is different when the joint is subjected to elevated or cold temperature conditions. Comprehensive experimental studies have shown that the clamp-up force relaxation in composite-aluminum (C/Al) and composite-steel (C/St) bolted joints is significantly different and highly variable [21–23]. The experimental study involved testing C/Al and C/St joints using both protruding head and countersunk head bolts over a 3 month period under ambient and elevated temperature (62°C). The C/Al and C/St joints showed 45% and 30% clamp-up force relaxation, respectively for 2,000 h, while the composite-to-composite joint had 55% relaxation. It was concluded that using a countersunk bolt did not affect the relaxation, when compared to a protruding head bolt. Significant thermal response was observed from the above joints as expected, because of the coefficient of thermal expansion mismatch between the materials. Structural health monitoring methods which come under the umbrella of structural vibration analysis have been successfully used to detect the clamp-up force relaxation in a large hybrid (C/St) structure [24]. Three different methods for assessing the change included: (1) fundamental model properties; (2) transfer functions; and (3) transmittance function using a piezoelectric actuator bonded to the composite panel to deliver the controlled vibration. Experiments involved detecting the loosening of bolts using the above three methods on a 622 mm

square composite plate joined to a steel plate with 16 bolts at its perimeter in two ways: first, by reducing torque of only one bolt, and second where the torques in all the bolts were reduced by the same amount. It was concluded that the transmittance function was the most promising method of the three in reliably detecting a single bolt loosening.

Most of the above studies were carried out without external static or dynamic loads acting on the joint. Bickford [25] suggests that external vibrations on any bolted joint will increase the clamp-up force relaxation because of wear and hammering. After sufficient pre-load is lost, friction forces drop below a critical level and the nut actually starts to back off and shake loose. With higher initial pre-load, longer or more severe vibration is required to reduce pre-load to the critical point at which back-off occurs. In fact, in some circumstances, if the pre-load is high enough to start with, nut back-off will never take place. It is not known if these observations apply to composite bolted joints. Hence, an effort has been made to determine the clamp-up force relaxation in a single composite bolted lap joint subjected to static and dynamic loads. The focus of the current investigation was to characterize the effects of various clamping loads (bolt preloads), external static loads and dynamic beam loads on relaxation in a composite bolted joint under combined bending and shear loads (3 point bending). An attempt was also made to back out the effect of viscoelasticity on relaxation by comparing experimental relaxation curves for a composite bolted joint with those of a steel joint, which does not exhibit viscoelastic behavior at room temperature.

5.2 Experimental Set-up

The composite specimen used for the test was made out of unidirectional P2254-20-305 T800 carbon/epoxy prepreg tape from Toray Composites America, Inc. A total of 48 layers of prepreg were laid on top of each other in the mold along with bleeder cloth and release fabric. The mold assembly was placed in the molding chamber of a TMP autoclave-style vacuum press. After curing, the thickness of the sample was 7.75 mm. There was no post curing cycle. After removing the laminate from the mold assembly, it was cut into two-piece rectangular beams of 269.87 mm × 25.4 mm and machined with a diamond cutting tool to the required dimensions as shown in Fig. 5.2. The joint was clamped together by a standard hexagonal head cap screw steel bolt with built in strain-gages (Strainsert®, 9.525 mm or 3/8 in. in diameter, model: SXS-FB) and washers (19 mm diameter). The joint was subjected to 3-point bending using an Enduratec servo-pneumatic testing machine. The design of the specimen support was selected in such a way to maintain combined bending and shear loading.

The joints were clamped with three different bolt preloads, 4,200 N, 5,050 N and 7,850 N, which correspond to 12.5%, 15% and 23.5%, respectively, of the maximum manufacturer recommended tensile load in the instrumented bolt. The corresponding through-the-thickness compressive stresses generated in the composite specimen were approximately 25%, 29% and 45%, respectively of the estimated transverse compressive strength of the composite. After applying an initial preload to the composite bolted joint, the bolt load was monitored for a period of 30 h under the following conditions: (a) Preload only condition without application of external load, (b) preload and a static applied load of 250 N (combination of ramp and dwell) in the 3 point bend setup (Fig. 5.2) and (c) preload and a 250 N amplitude dynamic load in the 3 point bend setup at frequencies of 1 Hz, 2 Hz and 5 Hz. External static and dynamic load experiments were carried out using the 3-point bend fixture.
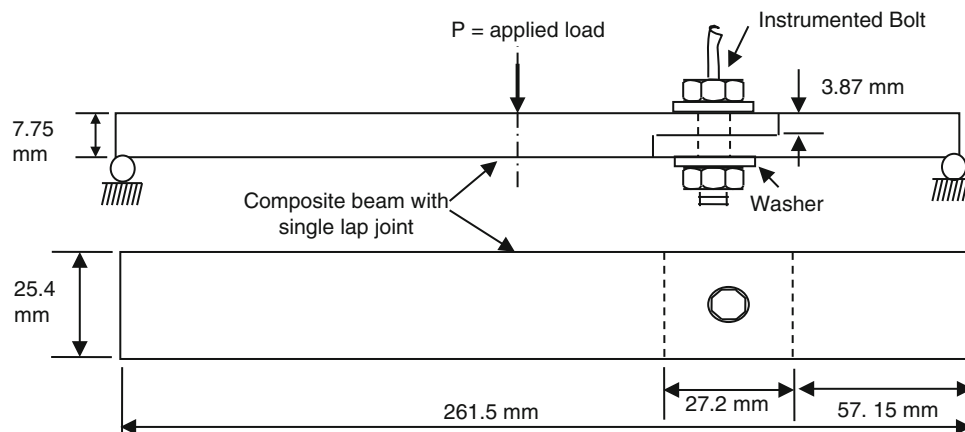

Fig. 5.2 Specimen configuration and three point bend set-up

Two separate data acquisition systems were used; one for the instrumented bolt and another to control the Enduratec servo-pneumatic testing machine and also to record the beam load and displacement values. A stability check on the data acquisition system was carried out by monitoring the signal from the instrumented bolt for a period of 30 h without the application of load to the bolts. The drift in the signal for the above period was less than 1%. Also, the drift in the signal was taken into account when the percentage relaxation was calculated. Preload only experiments were also conducted on a steel joint having the same dimensions as those of the composite joint. The bolt load was monitored for a period of 30 h using the same 3-point bend set-up and the instrumented bolt for preloads mentioned above.

5.3 Experimental Results

5.3.1 Effect of Preload Only Conditions on Relaxation in Composite and Steel Joints

Experimental bolt load relaxation results for composite bolted joints with initial preloads of 5,050 N and 7,850 N for preload only condition (i.e. no external load) are shown in Fig. 5.3, where the normalized bolt load is the instantaneous load divided by the initial load. It is clear from the results that for both steel and composite bolted joints, the magnitude of relaxation decreases with increasing bolt preload. However, for steel joints, the magnitude of relaxation is less than that of the composite joints. By comparison with the steel joints, some additional relaxation due to viscoelastic behavior in the composite joint was expected. Relaxation of approximately 3.0% and 2.5% was observed after 30 h in the composite joints preloaded to 5,050 N and 7,850 N, respectively, whereas the corresponding relaxation in the steel joint was approximately 1.9% and 1.75%, respectively. Numerical results from finite element analysis (FEA) will be discussed later.

5.3.2 Effect of Static External Loading Conditions on Relaxation in Composites Joints

Figure 5.4 shows the effect of a 250 N static beam load on bolt load relaxation in the composite bolted joint under the 3 point bend setup. It is observed that the magnitude of relaxation decreases with increasing bolt preload. However, when compared with the preload only condition, the bolt load relaxation increases for lower preloads (5,050 N) and the bolt load relaxation decreases for higher preloads (7,850 N) by approximately 0.5%, and the result for the lower preload (4,200 N) seems inconsistent with that trend.
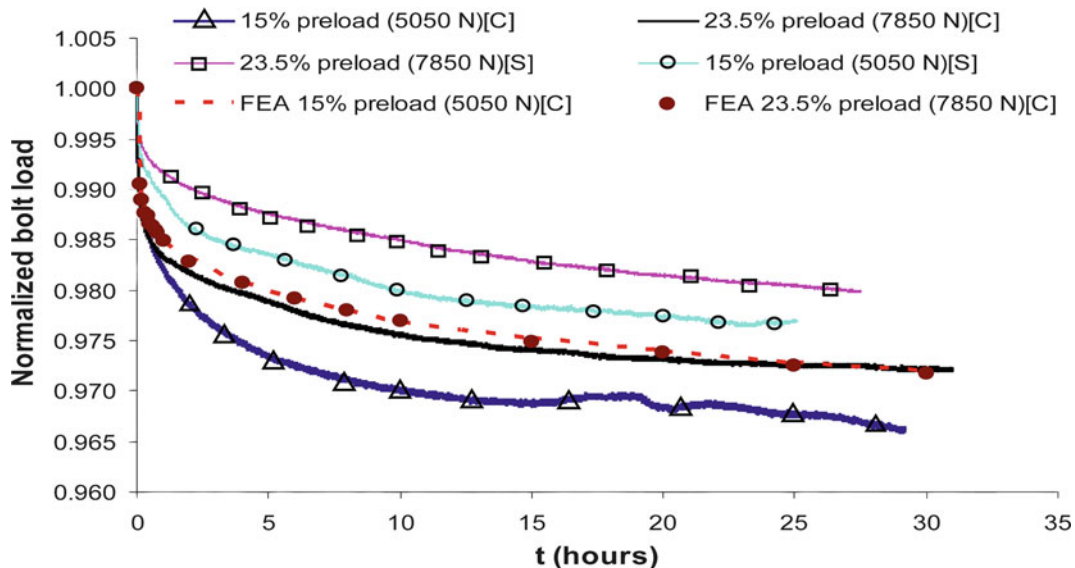

Fig. 5.3 Bolt preload relaxation in composite and steel joints for preload only condition without any external beam load (Note: *S* = Steel joint, *C* = Composite joint)
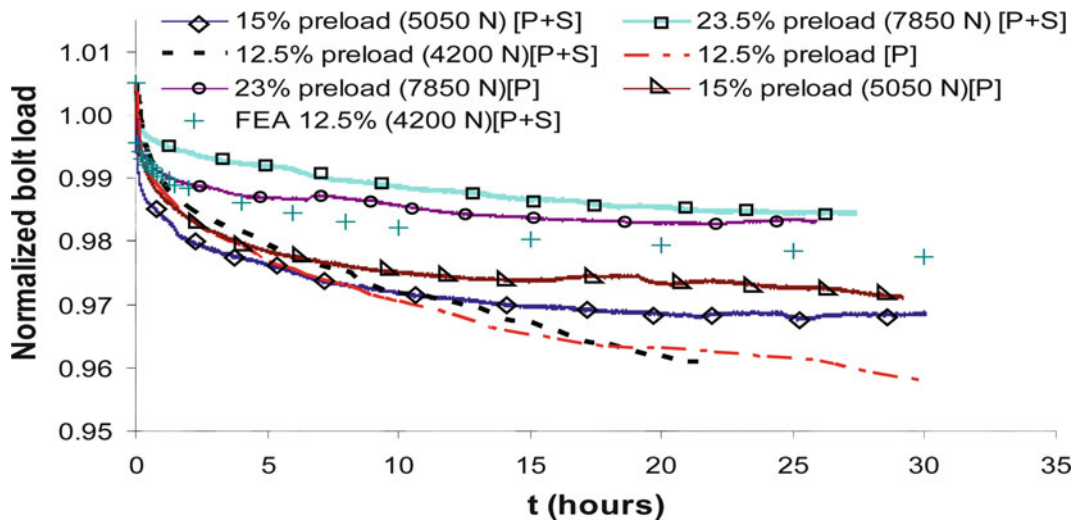
Fig. 5.4 Bolt preload relaxation in composite joints for preload only and preload with a static external beam load of 250 N (Note: P = preload only condition, $P + S$ = preload + static 250 N beam load)
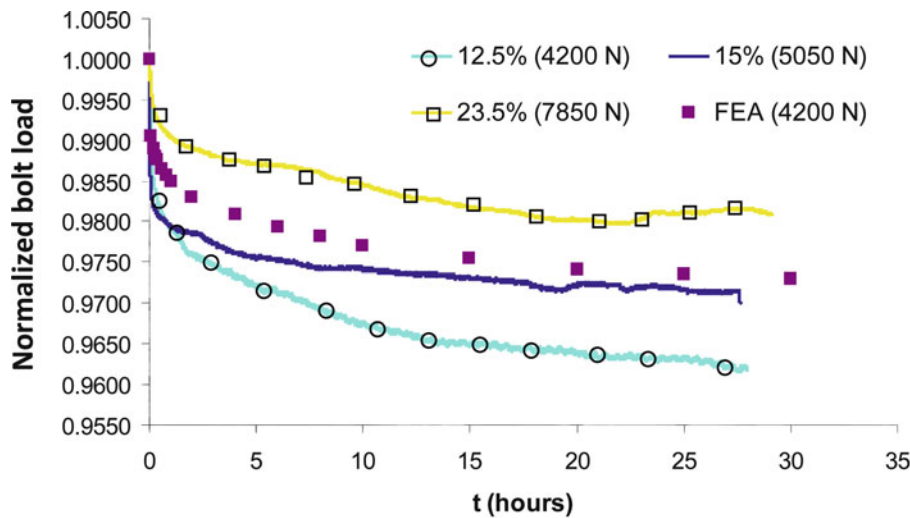

Fig. 5.5 Bolt preload relaxation in composite joints for preload with a dynamic external beam load of 250 N at 1 Hz

5.3.3 Effect of Dynamic Loading Conditions on Relaxation in Composites

Figures 5.5 and 5.6a, b show the effects of dynamic load at 1 Hz, 2 Hz and 5 Hz, respectively, on bolt load relaxation in the composite bolted joint under the 3 point bend setup. It is observed that at 1 Hz frequency (Fig. 5.5), the magnitude of relaxation decreases with increasing bolt preload. However, as the frequency of external beam load is increased to 2 Hz and 5 Hz (Fig. 5.6a, b), it is observed that the magnitude of relaxation tends to increase for both preloads. For lower preload (5,050 N) the reduction in the bolt load is significant during the initial stages of the experiment, and the rate of relaxation decreases with time, however, for higher preload the relaxation is higher. The increase in the rate of relaxation at higher frequencies of excitation may be due to the increase in temperature at the joint interfaces due to frequency-dependent frictional sliding and heating. The specimen configuration was not suitable for monitoring the temperature at the interface during the experiment. When the relaxation in bolt load due to applied dynamic load at 2 Hz and 5 Hz is compared with those due to applied static loads, it is observed that for lower preload (5,050 N) the applied static load increases the bolt load relaxation whereas for higher bolt preload (7,800 N) the bolt load relaxation decreases.
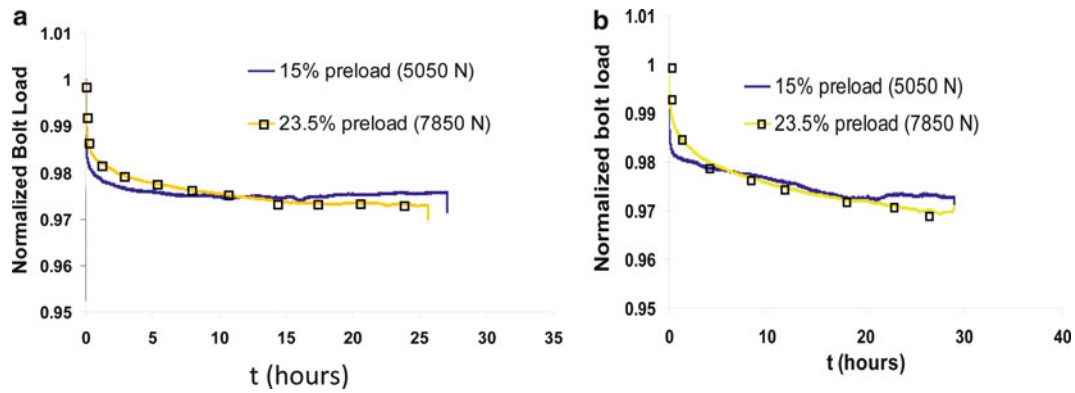
Fig. 5.6 Bolt preload relaxation in composite joints for preload with a dynamic external beam load of 250 N at (**a**) 2 Hz (**b**) 5 Hz
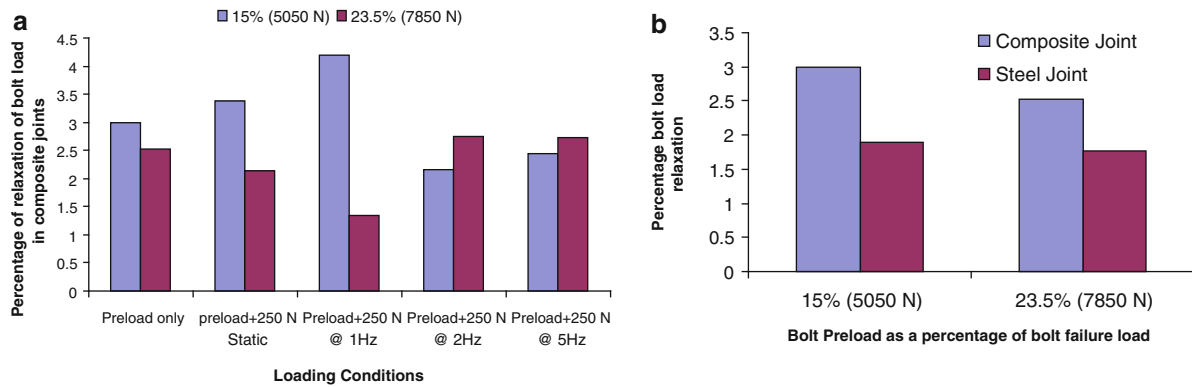

Fig. 5.7 (**a**) Effect of external beam load on bolt load relaxation in composite bolted joints for a period of 30 h (**b**) comparison of relaxation in composite and steel joints for a period of 30 h under preload only condition

A comparison of the bolt load relaxation in composite joints at the end of the 30 h duration is shown in Fig. 5.7a for two preloads with different external loading conditions. It is observed that for any external loading condition, the bolt load relaxation decreases with increasing initial bolt preload. These findings emphasize the importance of preload selection. For higher preload (7,850 N) the bolt load relaxation increases with increasing frequency of excitation, which could be partly due to an increase in the temperature at the interface due to frictional heating. Comparing the bolt load relaxation in steel and composite joints for the duration of 30 h (Fig. 5.7b), it is observed that only about 1/3 of the total relaxation in the composite joint is due to viscoelastic behavior of the polymer matrix material in the composite, while the remaining 2/3 is apparently due to the other relaxation mechanisms such as plasticity and/or slip in the bolt threads, which probably occur in steel joints as well.

5.4 Numerical Studies and Results

In this section, a brief summary of finite element analysis (FEA) simulations is given. For more detailed explanations of material characterization and complete FEA results, see [26]. The purpose of FEA is to develop predictive numerical models, and to promote a more meaningful interpretation of the experimental results. Hypermesh® 5.0 [27] was used to develop a three-dimensional (3D) FEA model of the composite bolted joint (see Fig. 5.8), and post-processing the results. ABAQUS® V 6.3 Standard 3-D [28] was used predict the bolt load relaxation using the quasi-elastic analysis. A global–local submodeling technique was used to model the bolted composite joint, where the displacements around the bolted joint section in the global model (a one-piece beam with no bolt) are used to drive the refined local model. This technique has the advantage that more detailed results in the vicinity of the bolted joint can be obtained with fewer elements than with the full model. All models were developed using C3D8 and C3D6 type 3-D solid elements. Since the model is symmetric about the

Fig. 5.8 Bolt FEA model
(Local)
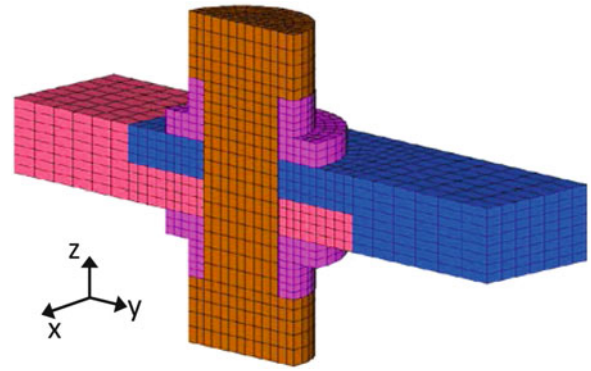
vertical midplane of the beam, only a half model was used, and symmetric boundary conditions were applied. The threads in the bolt were neglected in the FEA models, and the bolt was assumed to be a solid cylinder. Thus, possible bolt load relaxation due to plastic deformation and/or thread slip in the threads was not included in the models. The solid bolt simulation requires that contact surfaces be defined between all the surfaces that are in contact, and these surfaces were modeled using the contact pair approach in ABAQUS. The contact pairs are defined from free element faces. Since the sliding between the surfaces was expected to be small, the 'small sliding' option was used in all analyses. Friction coefficients were set to 0.2 for all contact surfaces, as used by Ireman [29].

5.4.1   Time Dependent Material Property Characterization

The three-dimensional (3-D) elastic lamina properties needed for the finite element analysis were calculated from composite micromechanics equations [30] (for example: the rule of mixtures to calculate the longitudinal modulus and Tsai-Hahn equations to calculate the transverse modulus and shear modulus) using the fiber and matrix properties together with the following assumptions: (1) the fibers are linearly elastic, (2) the matrix is linearly viscoelastic, with its creep compliance described by a power law, (3) the composite is specially orthotropic and transversely isotropic, and (4) the viscoelastic response depends only on the time elapsed since application of the load (i.e. the material is assumed to be non-aging). The analysis consisted of three parts: first, since the viscoelastic creep and relaxation data for the epoxy resin used in the prepreg is not available, Beckwith's [31] measured linear viscoelastic properties for Shell 58–68 epoxy at 75° F were assumed. Next, these properties were used in the FEA to predict the bolt load relaxation for an epoxy beam under different loading conditions using the quasi-elastic approach (for model validation see [26]). Since ABAQUS viscoelastic modeling capability is limited to isotropic materials, it was necessary to validate the quasi-elastic approach (explained in the next section). Lastly, Beckwith's [31] creep test results were extrapolated out to 50 h from the available data, by using the empirical power law equation for creep compliance:

$$D(t) = D_0 + D_1 t^n \tag{5.1}$$

where, from [31],

$D(t)$ = time dependent isotropic creep compliance of matrix
D_0 = initial elastic compliance of matrix = 2.726×10^{-4} (MPa)$^{-1}$
D_1 = creep coefficient of matrix = 1.0×10^{-3} (MPa)$^{-1}$ (min)$^{-n}$
t = time in minutes
n = dimensionless creep exponent = 0.19

The time-dependent viscoelastic properties of the composite joint were assumed to depend only on the time-dependent properties of the epoxy matrix material. Based on the linear viscoelastic assumption, a time-dependent matrix modulus, $E_m(t)$, was estimated from the following equation:

$$E_m(t) \approx \frac{1}{D(t)} \tag{5.2}$$

Table 5.1 Micromechanics estimate of time-dependent material properties for unidirectional carbon/epoxy[a]

Time (Hrs)	$E_m(t)$ (GPa)	$E_1(t)$ (GPa)	$E_2(t) = E_3(t)$ (GPa)	$G_{12}(t) = G_{13}(t)$ (GPa)	$v_{12}(t) = v_{13(t)}(t)$ $= v_{23}(t)$	$G_{23}(t)$ (GPa)
0	3.662	134.5	12.07	3.612	0.30	2.535
1	3.607	134.4	11.66	3.469	0.307	2.446
2	3.515	134.4	11.55	3.449	0.308	2.434
4	3.495	134.4	11.51	3.428	0.309	2.421
6	3.482	134.4	11.48	3.414	0.309	2.412
8	3.473	134.4	11.45	3.403	0.310	2.405
10	3.465	134.4	11.40	3.395	0.310	2.40
15	3.450	134.4	11.37	3.379	0.311	2.390
20	3.439	134.4	11.34	3.366	0.312	2.382
25	3.430	134.4	11.32	3.356	0.312	2.376
30	3.422	134.4	11.55	3.348	0.313	2.371

[a] Toray Composites America T800 carbon fibers with assumed viscoelastic compliance for Shell 58–68 epoxy matrix material [31]

It was assumed that the power law constants; D_0, D_1 and n at room temperature are the same as those measured by Beckwith for Shell 58–68 epoxy [31]. By using these constants and the power law, the time-dependent creep compliance, $D(t)$, for the epoxy material was calculated. The time-dependent Young's modulus of the matrix material, $E_m(t)$, (see Table 5.1) was found from Eq. 5.2. The tensile modulus data for T800 carbon fibers was obtained from the fiber manufacturer, Toray Composites America, Inc. as $E_f = 294$ GPa and was assumed to be independent of time. Viscoelastic properties of the lamina (i.e., longitudinal modulus $E_1(t)$, transverse moduli $E_2(t)$ and $E_3(t)$, Poisson's ratios $v_{12}(t)$, $v_{13}(t)$ and $v_{23}(t)$, longitudinal shear modulus $G_{12}(t)$, and transverse shear moduli $G_{13}(t)$ and $G_{23}(t)$) were estimated using elastic fiber properties and time-dependent viscoelastic resin properties through an application of the Elastic-Viscoelastic Correspondence Principle to the micromechanics equations [30] with a fiber volume fraction, $v_f = 0.45$ (see Table 5.1). The fiber volume fraction for the composite laminate was indirectly estimated using a combined experimental/numerical technique. Measured load–displacement response from static 3 point bend tests was compared with the predicted response (FE models) initially assuming the fiber volume fraction to be 0.6. The difference between the predicted and measured response was then minimized using fiber volume fraction as curve fitting parameter. These properties were then used in the FEA to calculate the bolt load relaxation. Due to the limitations of ABAQUS [28], the quasi-elastic approach [30] was used to predict the bolt load relaxation for the orthotropic composite beams. In this approach, the viscoelastic solutions were approximated by a series of elastic solutions corresponding to different elastic properties at different times, while the stresses were assumed to be constant within each time increment.

As in the experiments, the external load was applied as a concentrated nodal force at midspan. pre-tension in the bolt was applied in a separate loading step by defining a pre-tension section in the bolts. Assembly loads were transmitted across the pre-tension section by means of a pre-tension node. Preload was applied by giving an initial displacement (in the direction parallel to the bolt axis) to this node. Bolt preload was maintained by using the fixed option under boundary conditions, and was monitored by checking the total force output on that node. The model geometry and boundary conditions were chosen to simulate the experiments, as shown in Fig. 5.2. For the composite beams, both experiments and FEA (using the global–local model and quasi-elastic approach) were conducted, but only experiments were conducted for steel joints.

Bolt load relaxation was predicted for a period of 30 h in composite bolted joints using a quasi-elastic analysis and the material properties listed in Table 5.1 for various preload under the following types of loading: (1) bolt preloading in the absence of external beam loading, (2) bolt preload in the presence of a static beam load of 250 N, and (3) bolt preload in the presence of dynamic loading of amplitude 250 N at a frequency of 1 Hz. The dynamic beam load was applied using the periodic loading option in ABAQUS for 5 cycles under each quasi-elastic step and mean bolt load data was recorded in each case.

The predicted bolt load relaxation captures the relaxation in composite joints and is well within the measured relaxation curves (Fig. 5.3). The relaxation in bolt load is predicted using the quasi-elastic approach with the material properties listed in Table 5.1. It is observed from Fig. 5.3 that the predicted relaxation is not affected by increasing preloads, but the relaxation is higher than that measured in steel joints. This contradicts the experimental observation that relaxation decreases with increasing bolt preload. There are several possible reasons for this disagreement. First, the material model does not capture the viscoelastic effects in the polymer matrix material at the micromechanical level. The micromechanical analysis referred to in the discussion following Eq. 5.2 was based on "mechanics of materials" type models which do not take into account the details of the in-situ micromechanical stress and strain distributions in the viscoelastic polymer matrix. A 3-D finite element

micromechanics model which takes into account the micromechanical geometry is needed to accurately simulate the effects of such parameters as boundary conditions at the bolt-composite interface on the viscoelastic relaxation of the composite.

Figures 5.4 and 5.5 show the comparison of predicted bolt load relaxation for composite joints under external static and dynamic loads. Again, the predicted relaxation falls within the measured relaxation curves for both static and dynamic loads. Also, it is observed that the predicted bolt loads are shifted slightly with the application of the static and dynamic beam loads, but otherwise the relaxation curves are not significantly affected by the external loads. Again, the mean bolt load is plotted for the dynamic analysis.

5.5 Conclusions

- Experiments have been employed to study the effects of various bolt preloads, along with the effects of static and dynamic external loads on bolt load relaxation in composite bolted joints.
- Experiments show that for any external loading condition the bolt load relaxation decreases with increasing initial bolt preload, and these findings emphasize the importance of bolt preload selection.
- If the bolt preloads are small enough (as a percentage of bolt failure load), applied static and dynamic beam loads at 1 Hz frequency increase the magnitude of bolt load relaxation. However, for higher bolt preloads the bolt load relaxation decreases for both static and dynamic loads.
- It is observed that increasing the frequency of the external dynamic load from 1 to 5 Hz increases the rate of relaxation, and that the friction-induced heating may be at least partially responsible for this effect.
- Finite element models for bolt load relaxation in bolted composite joints based on a global/local quasi-elastic approach show reasonably good agreement with experiments except that the experimentally observed decrease in relaxation with increased bolt preload is not predicted by the models.
- The FEA predictions of bolt load relaxation agree well with the experimental observations when subjected to external static and dynamic loads, however, more detailed modeling of the polymer matrix behavior at the micromechanical level and possible time-dependent boundary conditions at the bolt-composite interface are needed to understand the experimentally observed relationship between bolt preload and bolt force relaxation.
- Comparing the bolt load relaxation in steel and composite joints for the duration of 30 h, it is clear that only about 1/3 of the total relaxation in the composite joint is due to viscoelastic behavior of the polymer matrix material, while the remaining 2/3 is apparently due to the other relaxation mechanisms such as plasticity and/or slip in the bolt threads, which probably occur in steel joints as well.

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