Research Article

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Research on preload relaxation for composite pre-tightened tooth connections

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Abstract: Preload is the primary reason why pre-tightened tooth connections (PTTC) can transfer relatively large loads. However, creep of the composite would cause the preload relaxation, resulting in reducing bearing capacity of the connection. To study the preload relaxation of PTTC caused by the creep of composites, a prediction formula is deduced by converting the viscoelastic problem to an elastic problem using Laplace transform. Meanwhile, long-term experimental research on the preload relaxation of composite pre-tightened tooth connection with different initial preloads and different geometry sizes was made. The theoretical results are compared with experimental data obtained by long-term experiment, and the results indicate that the calculation formula can predict the preload relaxation well in linear viscoelastic state. The preload relaxation mainly occurs at the beginning of loading and it tends to be steady in the middle and later periods.

Keywords: composite pre-tightened tooth connections, creep, preload relaxation, theoretical research, long-term experiment

1 Introduction

Composite pre-tightened teeth connection is a novel composite connection technology [1]. this connections technology are stripe-shaped teeth manufactured at the connection end of a composite with well-matched teeth on the metal connected to the composite. The preload q exerted

on the composite teeth after assembling the metal and composite can improve the composite interlaminar shear strength, making the joint transfer a larger load which is shown in Figure 1. The external load F is transferred via the shear stress τ of the shear surface of the composite teeth and the friction force f at the connection surface. When the load F is small, the load is transferred by the friction force. When the load F is large, the end of the composite tooth bears the compressive stress and begins to transfer the load, and the bearing capacity of the joint mainly depends on the capacity for bearing interfacial shear. Research showed higher connection efficiencies of PTTC of up to 70% for thick tubes. At the same thickness, the bearing capacity of the composite tube pre-tightened teeth connection is higher than that of the adhesive connection [1]. Due to high connection efficiencies, this connection technology has been applied in composite space truss structures and composite plane truss structures. The findings demonstrate that the advantages of the composite can be

Figure 1: Composites pre-tightened tooth connections

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capitalized by the composite pre-tightened tooth connection and this technology can satisfy the different directions connection of composite tube via bolt or weld connection of metal [2–5].

Preload is the major reason why composite PTTC can transfer relatively large loads. It does not only enhance shear strength between composite materials, but also enables the connection to offer larger friction during force transfer [6]. The research show that the preload also significantly affects the strength of composite bolt connection. Hart-Smith reported that the preload has a direct effect on joint bearing strength, with a 3500 lb clamp-up force increasing the joint strength by as much as 28% over that of a finger-tight joint [7]. Sun *et al.* presented the important effect of clamp-up force on bolt strength through finite element analysis and experimental validation [8]. No matter composite PTTC and composite bolt, after the joint assembled the preload q is always exerted perpendicular to the fiber of the connection composite, even if external loads are not present. Because of creep of the composite, the preload q exerted on the composite changes over time. And this change will affect the bearing capacity of composite joint [9]. Therefore, apart from determining the magnitude of preload q at the assembling stage of the joint, the preload relaxation caused by composite creep should be considered when composite PTTC and composite bolt are designed. Currently, most researches on preload relaxation of composite joints mainly focus on composite bolt connections. Horn and Schmitt observed that by increasing clamp-up force the joint bearing failure load increased by as much as 28%. Clamp-up force relaxation was also monitored and 6–16% relaxation from the initial clamp-up force was observed for short duration (1400 h) and long duration (100,000 h), respectively [10]. Thoppul *et al.* comprehensively reviewed several key issues affecting the time-varying preload relaxation of composite bolt connections [11, 12]. Caccese *et al.* conducted experimental research on preload relaxation of various connections including composite/composite, composite/aluminum, aluminum/aluminum, and composite/steel at room temperature [13]. Shivakumar performed a series of 100 d durability assessments on preload relaxation of composite connections under three different constant environments, namely dry/room temperature, water absorption 0.46%/room temperature, and dry/high temperature (66°C). Moreover, Shivakumar also constructed a classic preload relaxation model regarding the transitional creep characteristics of materials as the object, which is able to determine parameters based on short-term relaxation data and extrapolates long-term relaxation behavior [14]. By the research on preload relaxation of composite bolt, it can be obtained

that these types of connections can easily lose their initial preload because bolting typically stresses the composite in the through-the thickness direction, where the mechanical behavior of the composite material is dominated by the viscoelasticity of the matrix material. The potential impact of this preload loss in the connection would lead to catastrophic consequences. thus, it is important to develop a suitable prediction methodology that can evaluate the joint relaxation over time [15, 16]. however, a few prediction methodologies on preload relaxation on composite joint were developed. And the above-mentioned studies primarily focused on composite bolt connections without considering preload relaxation of PTTC.

The main objective of this work is to research preload relaxation of PTTC by the theory and experiment at room temperature, when the external loads are not exerted on the joint. In theoretical derivation, a formula for calculating preload relaxation of the joint over time is deduced by converting the composite viscoelastic constitutive relation to the elastic constitutive relation using Laplace integral transform. To verify the obtained formula and further study on the preload relaxation of the joint, long-term experimental researches of the preload relaxation were conducted at room temperature. The results show that the formula derived by this paper can effectively predict preload relaxation of composite connection. and the preload relaxation of PTTC mainly occurs at the beginning of loading and becomes steady over time. So, When the bearing capacity of joint is calculated, the preload relaxation should be considered. This theoretical derivation not only can be applied in the preload relaxation of composite PTTC, but also can be used in the preload relaxation of composite bolt connection.

2 Theoretical calculation of preload relaxation of PTTC

When the effects of composite creep on preload relaxation is researched, composite is usually considered as viscoelastic materials. Viscoelastic material and elastic material have their own different constitutive relations. The elastic constitutive equations are a special case of the viscoelastic constitutive equations, there are corresponding principles between the elastic constitutive relation and the viscoelastic constitutive relation [17]. In this study, to the obtain preload relaxation formula of the joint, the viscoelastic material properties of composite were converted to an elastic problem using Laplace integral transform. When the formula under the elastic condition is deduced,

the formula of preload relaxation can be obtained by the inverse calculation.

2.1 Laplace integral transform

Integral transform is that a function is transformed to another function by the integration calculation. For example, any function $f(x)$ in function Class A is multiplied by a specified two-variable function $K(x, p)$ and then the integral calculated is performed.

$$F(p) = \int_a^b f(x)K(x, p)dx \quad (1)$$

By doing so, the function $f(x)$ in function Class A can be converted to the function $F(p)$ which is in another Class B, where the domain of integration is certain.

The purpose of solving differential equations using integral transform can be described as follows: if it is difficult to solve x by original function, one can solve X by its mapping function first and then x can be obtained by X .

For example, define a function $f(t)$ of a real independent variable t in the interval $(0, +\infty)$, and multiply it by e^{-pt} , where p is a complex value. Then, integrate t from 0 to $+\infty$. If this improper integral converges, a complex-value function $F(p)$ of the complex number p is obtained.

$$F(p) = \int_a^{+\infty} f(t)e^{-pt} dt \quad (2)$$

This transform is called Laplace transform, which is denoted by $L(f(t))$.

If function $f(t)$ satisfies the following conditions:

1. When $t < 0$, $f(t) = 0$;
2. $f(t)$ satisfies the XX condition in every finite interval $0 \leq t \leq T$;
3. With the increase in t , the magnitude of the function $f(t)$ increases, but remains smaller than some exponential functions.

That is, there exist constants and such that $|f(t)| \leq Me^{s_0 t}$. Then, the mapping function $F(p)$ of original function $f(t)$ exists in the half-plane $\text{Re } p > s_0$, and this function is analytical.

2.2 Basic method of corresponding principles

To study displacement, stress, and strain of viscoelastic bodies under loading, three equations, the viz. balance

condition, geometric relation, and constitutive equation are required, where stress and displacement are also need to satisfy certain boundary conditions and initial conditions.

Geometric equation:

$$2\varepsilon_{ij}(t) = u_{i,j}(t) + u_{j,i}(t) \quad (3)$$

Balance equation (equation of motion):

$$\sigma_{ij,j}(t) + F_i(t) = 0 \quad \sigma_{ij,j}(t) + F_i(t) = \rho \frac{\partial^2 u_i}{\partial t^2} \quad (4)$$

Constitutive equation:

$$s_{ij}(t) = 2 \int_{-\infty}^t G(t-\tau) \frac{\partial \varepsilon_{ij}(\tau)}{\partial \tau} d\tau \quad (5)$$

$$\sigma_{ii}(t) = 3 \int_{-\infty}^t K(t-\tau) \frac{\partial \varepsilon_{jj}(\tau)}{\partial \tau} d\tau$$

Where $\sigma_{ij}(t) = s_{ij}(t) + \frac{1}{3} \delta_{ij} \sigma_{kk}(t)$, $s_{ii} = 0$

$\varepsilon_{ij}(t) = e_{ij}(t) + \frac{1}{3} \delta_{ij} \varepsilon_{kk}(t)$, $e_{ii} = 0$

Initial boundary conditions are:

$$u_i(t) = \varepsilon_{ij}(t) = \sigma_{ij}(t) = 0, -\infty < t < 0 \quad (6)$$

$$\sigma_{ij}(t)n_j = S_i(t), B_\sigma$$

$$u_i(t) = \Delta_i(t), B_u$$

If the Laplace transform of the time variable exists and the given boundary surfaces B_σ, B_u are both constant (not time dependent), for a linear viscoelastic body, Laplace transform can be performed using Eq. (2), and the following expression can be obtained.

Geometric equation:

$$2\bar{\varepsilon}_{ij}(s) = \bar{u}_{i,j}(s) + \bar{u}_{j,i}(s) \quad (7)$$

Balance equation:

$$\bar{\sigma}_{ij,j}(s) + \bar{F}_i(s) = 0 \quad (8)$$

Constitutive equation:

$$\bar{s}_{ij}(s) = 2s\bar{G}(s)\bar{\varepsilon}_{ij}(s) \quad (9)$$

$$\bar{\sigma}_{kk}(s) = 3s\bar{K}(s)\bar{\varepsilon}_{kk}(s)$$

where $\bar{s}_{ij}(s) = \bar{\sigma}_{ij}(s) - \frac{1}{3} \delta_{ij} \bar{\sigma}_{kk}(s)$, $\bar{s}_{ii}(s) = 0$

$\bar{\varepsilon}_{ij}(s) = \bar{e}_{ij}(s) - \frac{1}{3} \delta_{ij} \bar{\varepsilon}_{kk}(s)$, $\bar{\varepsilon}_{ii}(s) = 0$

Boundary condition:

$$\bar{\sigma}_{ij}(s)n_j = \bar{S}_i(s), B_\sigma \quad (10)$$

$$\bar{u}_i(s) = \bar{\Delta}_i(s), B_u$$

The above deduction describes a linear elastic problem of an object with material constants of $s\bar{G}(s)$ and $s\bar{K}(s)$, a surface force of $\bar{S}_i(s)$ at the boundary, given displacement of $\bar{\Delta}_i(s)$, and body force of $\bar{F}_i(s)$. So, the viscoelastic boundary value problem is the same as the elastic boundary value problem after transformation. The linear viscoelastic boundary value problem is a corresponding elastic problem in the Laplace transform space, which can be simplified to solve the linear viscoelastic boundary value problem.

2.3 Preload relaxation calculation of cylinder tooth connections

When the preload relaxation of pre-tightened tooth connections is investigated without external load, the elastic solution of preload on composite tube teeth is deduced first by force balance and compatibility of deformation of interfaces according to the theory of thick-walled cylinders. Then, based on the elastic solution and the corresponding principles, the preload relaxation for linear viscoelastic composite tube can be obtained [19].

For a thick-walled cylinder with an inner radius a and outer radius b under inner pressure p_1 and outer pressure p_2 , as shown in Figure 2, its radial stress σ_r , circular σ_{θ} , circular strain ε_{θ} , and radial displacement u for any point in the cylinder can be expressed by the following Eqs. (11), (12), and (13).

$$\begin{cases} \sigma_r = \frac{a^2 b^2 (p_2 - p_1)}{b^2 - a^2} \frac{1}{r^2} + \frac{a^2 p_1 - b^2 p_2}{b^2 - a^2} \\ \sigma_{\theta} = -\frac{a^2 b^2 (p_2 - p_1)}{b^2 - a^2} \frac{1}{r^2} + \frac{a^2 p_1 - b^2 p_2}{b^2 - a^2} \end{cases} \quad (11)$$

$$\varepsilon_{\theta} = \frac{1}{E} \left[-(1 + \nu) \frac{a^2 b^2 (p_2 - p_1)}{b^2 - a^2} \frac{1}{r^2} + (1 - \nu) \frac{a^2 p_1 - b^2 p_2}{b^2 - a^2} \right] \quad (12)$$

$$u = \frac{1}{E} \left[-(1 + \nu) \frac{a^2 b^2 (p_2 - p_1)}{b^2 - a^2} \frac{1}{r^2} + (1 - \nu) \frac{a^2 p_1 - b^2 p_2}{b^2 - a^2} r \right] \quad (13)$$

The PTTC of a composite tube consists of three different tube types. Before fabrication, the inner and outer radii of the inner metal tube are d and $a + \delta$, respectively. The inner and outer radii of the composite tube are a and b , whereas the inner and outer radii of the outer metal tube are b and c . Because of the interference fit δ between the inner metal tube and the composite tube, the pressure p will be exerted on the inner wall of the composite tube during fabricating. In addition, the pressure q is exerted on

Figure 2: A thick walled cylinder under inner and outer presses

its outer wall caused by the radial constraint of the outer metal tube. Correspondingly, the pressure q will be exerted on the inner wall of the outer metal tube and pressure p will be exerted on the outer wall of the inner metal tube (Figure 3). The pressure p and q are the preload of the joint.

The Poisson's ratio and elastic modulus for the outer metal tubes are E_1 . The Poisson's ratio and transverse elastic modulus for the composite tube are E_2 . And the Poisson's ratio and elastic modulus for the inner metal tubes are E_3 . For very small interference fit values, the outer radius of the inner metal tube can be considered as a . The radial displacement of the outer wall of the inner metal tube can be obtained by Eq. (13) as follows:

$$u_{1out} = \frac{-(1 + \nu_3)d^2 a q}{(a^2 - d^2)E_3} + \frac{-(1 - \nu_3)a^3 q}{(a^2 - d^2)E_3} \quad (14)$$

The displacement of the inner wall of the composite tube can be expressed as:

$$u_{2in} = \frac{1}{E_2} \left[\frac{-(1 + \nu_2)(p - q)ab^2}{(b^2 - a^2)} + \frac{(1 - \nu_2)(a^2 q - b^2 p)a}{(b^2 - a^2)} \right] \quad (15)$$

The displacement of the outer wall of the composite tube is:

$$u_{2out} = \frac{1}{E_2} \left[\frac{-(1 + \nu_2)(p - q)a^2 b}{(b^2 - a^2)} + \frac{(1 - \nu_2)(a^2 q - b^2 p)a}{(b^2 - a^2)} \right] \quad (16)$$

The radial displacement of the inner wall of the outer metal tube is:

$$u_{3in} = \frac{(1 + \nu_1)c^2 b p}{(c^2 - b^2)E_1} + \frac{(1 - \nu_1)b^3 p}{(c^2 - b^2)E_1} \quad (17)$$

The sum of the displacements of composite tube and outer metal tube at the junction is 0, and the sum of the

Figure 3: Diagram of three tubes under preload

Figure 4: Geometry of the composite pre-tightening force tooth connection

displacements of composite tube and inner metal tube at the junction is the interference fit δ . The obtained equation can be described as follows:

$$\begin{aligned} u_{2out} + u_{3in} &= 0 \\ u_{1out} + u_{2in} &= \delta \end{aligned} \quad (18)$$

The preload of the joint q between composite tube and outer metal tube can be acquired by solving the equation as

$$q = \frac{E_2^2 \delta M + E_2 \delta N}{E_2^2 W + E_2 F + H + L} \quad (19)$$

Where:

$$\begin{aligned} M &= \frac{(1 + \nu_1)c^2b}{(c^2 - b^2)E_1} + \frac{(1 - \nu_1)b^3}{(c^2 - b^2)E_1} \\ N &= \frac{(1 + \nu_2)pa^2b}{(b^2 - a^2)} + \frac{(1 - \nu_2)ab^2p}{(b^2 - a^2)} \\ L &= \left(\frac{-(1 + \nu_2)ab^2}{(b^2 - a^2)} + \frac{(1 - \nu_2) - b^2a}{(b^2 - a^2)} \right) \left(\frac{-(1 + \nu_2)a^2b}{(b^2 - a^2)} + \frac{(1 - \nu_2)a^3}{(b^2 - a^2)} \right) \\ W &= \left(\frac{(1 + \nu_1)c^2b}{(c^2 - b^2)E_1} + \frac{(1 - \nu_1)b^3}{(c^2 - b^2)E_1} \right) \left(\frac{-(1 + \nu_3)d^2a}{(a^2 - d^2)E_3} \right. \end{aligned}$$

$$\begin{aligned} &+ \frac{-(1 - \nu_3)a^3}{(a^2 - d^2)E_3} \Big) \\ F &= \left(\frac{-(1 + \nu_3)d^2a}{(a^2 - d^2)E_3} + \frac{-(1 - \nu_3)a^3}{(a^2 - d^2)E_3} \right) \left(\frac{(1 + \nu_2)pa^2b}{(b^2 - a^2)} + \frac{(1 - \nu_2)ab^2p}{(b^2 - a^2)} \right) \\ &+ \left(\frac{(1 + \nu_1)c^2b}{(c^2 - b^2)E_1} + \frac{(1 - \nu_1)b^3}{(c^2 - b^2)E_1} \right) \\ H &= \left(\frac{(1 + \nu_2)ab^2}{(b^2 - a^2)} + \frac{(1 - \nu_2)a^3}{(b^2 - a^2)} \right) \left(\frac{(1 + \nu_2)pa^2b}{(b^2 - a^2)} + \frac{(1 - \nu_2)ab^2p}{(b^2 - a^2)} \right) \end{aligned}$$

In this paper, the Poisson's ratio can be considered as constant. Replacing the Young's modulus perpendicular to fiber E_2 with $s\bar{E}_2(s)$ and replacing the magnitude of interference δ with $\frac{\delta}{s}$, one can obtain:

$$q = \frac{S\bar{E}_2(S)^2 \delta M + \bar{E}_2(S) \delta N}{S^2 \bar{E}_2(S)^2 W + \bar{E}_2(S) SF + H + L} \quad (20)$$

where $s\bar{E}_2(s)$ is the Laplace transform of the modulus of viscoelasticity perpendicular to the composite fiber.

Table 1: Material properties of test specimens

material	E_x (GPa)	E_y (GP)	E_z (GPa)	ν_{xy}	ν_{yz}	ν_{xz}	G_{xy} (GPa)	G_{zy} (GPa)	G_{xz} (GPa)
Composite	48	8.2	8.2	0.26	0.26	0.2	5.1	4.6	5.1
Aluminum alloy	68	68	68	0.3	0.3	0.3	-	-	-
Steel	210	210	210	0.3	0.3	0.3	113	113	113

Because creep test is easier to carry out than relaxation test, the creep flexibility of material is usually obtained, but the relaxation modulus of material is often used in application. There are the following mathematical relationships between creep flexibility and relaxation modulus in the Laplace space [20]:

$$\bar{E}_2(s)\bar{J}(s) = \frac{1}{s^2} \quad (21)$$

Relaxation modulus can be obtained by the creep flexibility of the material using the corresponding principle, and stress relaxation law for composite pre-tightened tooth connections can be researched.

The linear viscoelastic solutions of preload can be obtained from the inverse Laplace transformation of Eq. (20) as shown below:

$$q(t) = L^{-1}(\bar{q}(s)) \quad (22)$$

Relaxation trends of connection preload can thus be acquired from Eq. (22).

3 Experimental research on the preload relaxation of PTTC

To verify the theoretical deduction and evaluate the preload relaxation trends of composite PTTC, an experimental investigation was also conducted in this work with various initial preload values and geometries at room temperature. In these tests, preload was exerted on the connections by interferential fit. Due to the necessity of measuring connection strain for a relatively long period of time, stable data acquisition is critical. Compared with strain gauges, fiber Bragg grating sensors can offer greater stability. consequently, they were adopted for data collection in this study.

3.1 Specimen materials

- 1) Composite: the glass fiber composite tubes used were pultruded for the experiment. the fiber directions were generally 0 degrees. The fiber fraction

was approximately 65% per weight, of which approximately 89.15% was carbon fiber and 10.85% was combined mats. Material parameters are shown in Table 1.

- 2) Steel: Q345. Material parameters are shown in Table 1.
- 3) Aluminum alloy: T6061. Material parameters are shown in Table 1.

In Table 1, x is the along fiber direction, whereas y and z are perpendicular to the fiber directions. Compressive strength of composite perpendicular to the fiber directions is 110 MPa, and compressive creep flexibility perpendicular to the fiber directions was determined by the reference [20].

$$J(t) = 0.0176 - 0.000118369e^{-0.00000127737t} - 0.000189515e^{-0.00003564792t} - 0.00015765e^{-0.0000000339918t} - 0.000660752e^{-0.00000000975084t} - 0.00022307e^{-0.00000000762725t} - 0.000133366e^{-0.000000170653t} \text{ MPa}^{-1} \quad (23)$$

In the experiments, the inner metal tubes and the outer metal tubes of the joint were aluminum alloy and steel. and the joint and the dimension of the composite tubes were inner radius 44 mm, outer radius 52 mm, and wall thickness 8 mm. Based on the radial stress calculation formula for thick-walled cylinders, three groups of specimens with different metal tube dimensions and magnitudes of interference were designed, as shown in Figure 4. preload was exerted mainly by interferential fit of the inner metal tube, as shown in Figure 5. The outer steel tube and composite tube were first assembled via the composite tooth (Figure 5(a)). The inner metal tube was contracted by decreasing the temperature with liquid nitrogen and was then pushed into the composite tube. The inner metal tube then expands when its temperature was raised to room temperature. As a result, preload was exerted on the composite tube and the outer steel tube (Figure 5(b)). Table 2 shows the theoretically calculated initial preload values of the composite connections for the three groups of speci-

Table 2: Cylinder specimen with interferential fit

Serial	External metal tube (mm)	Inner metal tube (mm)	Magnitudes of interference (mm)	Initial preload (MPa)
A-L-3	60×52	44×35	0.08	25
A-M-3	65×52	44×35	0.10	38
A-H-3	70×52	44×30	0.10	50

Figure 5: (a) Metal tube installed into the composite tube (b) Diagram of interferential fit

mens under the corresponding magnitudes of interference at room temperature. As observed in the table, three initial preloads of 25 MPa, 38 MPa, and 50 MPa were designed.

As the composite tube of the connection was wrapped by the outer metal tube, it was difficult to measure the preload between composite tube and metal tube using sen-

Figure 6: Distribution of Fiber Bragg Grating sensor on the outer metal tube

sors. In this experiment, sensors were arranged around the outer steel tube to measure its circular strain, based on which preload between composite tube and metal tube can be calculated. The sensor distribution is schematically shown in Figure 6.

3.2 Test procedure

The inner tube was immersed into liquid nitrogen for two hours, and the temperature of the joint reaches -198°C . The outer metal tube and composite cylinder were assembled via the composite tooth. On the static testing machine, the inner tube taken out from liquid nitrogen was rapidly pushed into the composite tube, during which optical fiber sensors measured the circular strain of the outer tube (Figure 7). After being pushed to the pre-determined depth, the inner tube was fixed in the composite tube (Figure 8). Two sets of data were collected: a) circular strain of the outer tube during pushing of the inner tube, and b) circular strain evolution of the outer metal tube after the inner metal tube was pushed in, with a measurement duration of 8,000,000 s. The circle strains of PTTC are measured every minute in the first 12 hours, every hour in the following 12 to 100 hours, every six hours in the following 100 to

1000 hours and every 24 hours after 1000 hours, in the controlled environment of room temperature 25°C and a R.H. of 50%.

Figure 7: Measurements during the pushing process

Figure 8: Measurements after the pushing process

3.3 Analyses of test results

3.3.1 Analyses of the pushing process

A circular strain variation pattern of the outer metal tube during pushing of the inner metal tube is shown in Figure 9. As observed in this figure, circular strain of the outer tube monotonically increases at the beginning. When the end of inner tube is pushed through the location of optical fiber sensors, first steady state of circular strain exists and the circular strain is unchanged. After this stage, circular strain of the outer tube keeps on monotonically increasing. When the inner tube is completely pushed in, circular strain rapidly approaches second steady state. The location of inner tube pushed can be judged by the state of circular strain. Using Eq. (12), the test values of preload can be obtained by measured circular strain at the steady stage. And Table 3 shows the comparison of theoretical preload values obtained by Eq. (19) and the corresponding test values. As observed in this table, compared with the experimental data, the numerical model provides higher magnitudes of failure load with a difference of <16% to the test value. Thus, validity of the theoretical deduction is confirmed. Moreover, preload of specimen A-H-3 is smaller than that of specimen A-M-3, indicating that under the same magnitude of interference, a thicker metal tube wall leads to a greater preload.

3.3.2 Analyses of preload relaxation

Through measurements of circular strain of the outer metal tube, the evolution of preload of the composite outer wall can be obtained. The preload relaxation trends are

Figure 9: Strain of the three specimens during assembly

Table 3: Design values and test values of the outer tube circular strain and preload

Serial	Theoretical circular strain ($\mu\epsilon$)	Initial theoretical preload q_t (MPa)	Experimental circular strain ($\mu\epsilon$)	Initial experimental preload q_e (MPa)	$\frac{q_t - q_e}{q_t} \times 100\%$
A-L-3	645	25	640	23	8
A-M-3	584	38	496	32	16
A-H-3	534	50	473	44	12

Figure 10: Trends of specimen preload relaxation obtained from experiments

shown in Figure 10. For specimen A-H-3, preload relaxes to a maximum of 43% at 8000000 s; for specimen A-M-3, preload relaxes to a maximum of 45% at 8000000 s; for specimen A-L-3, preload relaxes to a maximum of 48% at 8000000 s. This suggests that with higher initial preload, a greater relaxation of preload is expected within the same period. Preload of all specimens sharply decreases in a relatively short period of time. A maximum 25% relaxation of preload is observed within 1000000 s, whereas the maximum relaxation is 23% in the later 7000000 s. Thus, it can be concluded that preload tends to relax more when initially exerted on the connection, while the relaxation becomes more stable over time.

Based on Eqs. (22) and (23), the theoretical preload relaxation functions for the three specimens are:

$$\begin{aligned}
 \text{Relax} = & -2.72205497310^{-27} e^{-0.001744789073t} \\
 & + 0.9999999998 e^{-0.001613742946t} \\
 & - 7.54521554810^{-25} e^{-0.000003651443519t} \\
 & - 1.83763049710^{-26} e^{-0.000002580697769t} \\
 & + 1.07521274210^{-30} e^{-1.82054908910^{-7}t} \\
 & - 8.08907573810^{-29} e^{-1.71489260910^{-7}t}
 \end{aligned} \quad (24)$$

$$\begin{aligned}
 & + 9.08882225310^{-31} e^{-3.78252156510^{-8}t} \\
 & - 7.59443780310^{-29} e^{-3.58634535410^{-8}t} \\
 & + 8.65018742810^{-31} e^{-9.00774396610^{-9}t} \\
 & - 8.12486692310^{-29} e^{-8.53652165410^{-9}t} \\
 & + 1.25958501810^{-30} e^{-1.44449297210^{-9}t} \\
 & - 1.38002010610^{-28} e^{-1.32752972010^{-9}t} \\
 & - 3.60764289510^{-28}
 \end{aligned}$$

A-M-3:

$$\begin{aligned}
 \text{Relax} = & 5.95512421510^{-28} \\
 & + 0.7702990196 e^{-0.001728559651t} \\
 & + 0.2297009802 e^{-0.001613510204t} \\
 & - 3.85659408810^{-25} e^{-0.000003653506543t} \\
 & + 1.26716662910^{-25} e^{-0.000002703990015t} \\
 & - 1.87099907510^{-30} e^{-1.82069161210^{-7}t} \\
 & + 1.50336648910^{-28} e^{-1.73143517810^{-7}t} \\
 & - 1.58142400810^{-30} e^{-3.78277176810^{-8}t} \\
 & + 1.38732309510^{-28} e^{-3.61853606010^{-8}t} \\
 & - 1.50474492710^{-30} e^{-9.00831132210^{-9}t} \\
 & + 1.45452553010^{-28} e^{-8.61769319210^{-9}t} \\
 & - 2.19090021710^{-30} e^{-1.44462539110^{-9}t} \\
 & + 2.40073686410^{-28} e^{-1.34873252010^{-9}t}
 \end{aligned} \quad (25)$$

A-H-3:

$$\begin{aligned}
 \text{Relax} = & 4.30381934810^{-27} e^{-0.001705804817t} \\
 & + 1000000000 e^{-0.001613050115t} \\
 & - 2.87751180610^{-25} e^{-0.000003657586734t} \\
 & + 1.84478693510^{-26} e^{-0.000002881107533t} \\
 & - 8.69686897010^{-31} e^{-1.82097290510^{-7}t} \\
 & + 8.85474732010^{-29} e^{-1.75266501810^{-7}t} \\
 & - 7.35425400010^{-31} e^{-3.78326608710^{-8}t} \\
 & + 7.99580377510^{-29} e^{-3.65901636410^{-8}t}
 \end{aligned} \quad (26)$$

$$\begin{aligned}
& - 7.00000968510^{-31} e^{-9.00942996410^{-9} t} \\
& + 8.17739140010^{-29} e^{-8.71754120510^{-9} t} \\
& - 1.01883609210^{-30} e^{-1.44488656010^{-9} t} \\
& + 1.30463206610^{-28} e^{-1.37418137510^{-9} t} \\
& + 3.05400198410^{-28}
\end{aligned}$$

Preload relaxation patterns of the three specimens can be obtained by Eqs. (24), (25), and (26). Figures 11-13 demonstrate the comparison of preload relaxation trends obtained by theoretical predictions and experiments. As can be seen, results from theoretical prediction and experimental test results show the same trends. That is, relaxation is more obvious in the initial stage, while approaching steady state in the later period. Due to experimental uncertainties, prediction results and experimental data of

Figure 11: Comparison of preload relaxation for A-L-3

Figure 12: Comparison of preload relaxation for A-M-3

Figure 13: Comparison of preload relaxation for A-H-3

specimen A-L-3 show fairly large discrepancies (up to 20%) within a certain interval, but congruence is again reached in the later period. For the other two specimens, discrepancies between theoretical values and test values are below 15% in any period, confirming the validity of the theoretical deduction. Therefore, the method proposed in this paper for calculating composite preload relaxation can provide effective predictions for joints.

3.4 Effects of cylinder geometry upon preload relaxation

The composite tube has an inner radius of 44 mm, an outer radius of 52 mm, and an interference of 0.1 mm between inner tube and composite tube. The outer radius of the outer metal tube was increased from 55 mm to 80 mm, and the inner radius of the inner metal tube was enlarged from 10 mm to 40 mm. Based on Eqs. (22) and (23), composite connection preload relaxation under different geometries at 5000 s is shown in Figure 14. As can be observed, under the same magnitude of interference and relaxation time, when the inner radius of the inner metal tube is 40 mm and the outer radius of the outer metal tube is 55 mm, connection preload declines to 78.5% of the initial value, which is the smallest preload relaxation. When the inner radius of the inner metal tube is 0 mm (i.e., inner metal tube is solid) and the outer radius of the outer metal tube is 80 mm, connection preload declines to 72% of the initial value, which is the largest preload relaxation. Thus, it can be concluded that preload exerted on the composite tube wall relaxes more when one uses a smaller inner radius for the inner tube and a larger outer radius for the outer tube. Preload exerted on the composite tube wall shows

Figure 14: Correlation between preload relaxation and geometries of inner and outer tubes

less obvious relaxation when employing a larger inner radius for the inner tube and a smaller outer radius for the outer tube. As a result, a combination of larger inner tube and smaller outer tube can effectively suppress the relaxation of preload.

4 Conclusion

In this paper, a method was proposed to predict preload relaxation of composite pre-tightened tooth connections. To verify the method, preload relaxation of composite PTTC was experimentally investigated under different initial preload values and geometries. Based on this study, the following conclusions are drawn:

- 1) When deriving the formula for calculating connection preload relaxation, the composite has mainly been considered as a viscoelastic material. the linear viscoelastic problem was converted to an elastic problem through the Laplace integral transform. Based on the theory of thick-wall cylinder elasticity, a formula for calculating preload relaxation of composite PTTC was obtained.
- 2) The methodology proposed can be used to predict the preload relaxation of composite pre-tightened tooth connections. The predictions obtained by the proposed model are in good agreement with experimental data. Theoretical predictions and test results

qualitatively display the same trends. To be more specific, it was found that relaxation is more obvious in the initial stage after loading, while approaching steady state in the later period. Due to experimental uncertainties, prediction results and experimental data of specimen A-L-3 show fairly large discrepancies within a certain interval, with the maximum level reaching 20%, but concur again in the later period. For the other two specimens, discrepancies between theoretical values and test values are below 15% in any period.

- 3) Under the same magnitude of interference and loading time, preload exerted on the composite tube wall relaxes more when a smaller inner radius for the inner tube and a larger outer radius for the outer tube are adopted. In contrast, preload exerted on the composite tube wall shows less obvious relaxation when a larger inner radius for the inner tube and a smaller outer radius for the outer tube are used. Therefore, a combination of larger inner tube and smaller outer tube can effectively suppress the preload relaxation.

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