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Numerical studies for stress loss on NiTi arch-wire in long term during orthodontic treatment

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ABSTRACT

This study presents quantified measures of stress loss occurred on NiTi arch-wire due to creep of teeth and stress relaxation of wire. Formulations for the stress loss of arch-wire due to creep and stress relaxation are adopted from prestressed concrete design, assuming that mechanical responses of arch-wire during orthodontic treatment procedure is similar to those of tendon for prestressed concrete beam. Stress relaxation and friction of NiTi arch-wire, and creep compliance of human teeth are obtained from the available literatures, while dry shrinkage is neglected in this study.

From the study, it is found that the stress loss formulations for prestressed concrete are adoptable to orthodontics, because 1) relaxation class of the arch-wire is similar to that of hot rolled and prestressing bars, and 2) ultimate creep coefficient of teeth is within the range of ultimate creep coefficient of concrete, which is 2 to 4.

It is expected that the suggested formulations can contribute to develop orthodontic treatment and device design by providing stress changes of arch-wire as functions of time without generating multiple FE models.

1. INTRODUCTION

The purpose of this study is to investigate the stress loss on NiTi archwire in long term during clinical orthodontic treatment. Towards that goal, formulations dealing with creep and stress relaxation of the prestressed concrete in architectural and civil engineering field are adopted to estimate stress loss on the archwire. In addition, fundamental initial stress value of teeth and wire is found out by using finite element method (FEM).

Many studies have focused on effect of orthodontic forces on tissues of teeth, periodontal ligament(PDL), and bone, from mechanobiological aspects. Lee(2013) studied about orthodontic force causing strain to the PDL and alveolar bone, which in turn released variety of cytokines, chemokines, and growth factors. As a result of the

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study, it was reported that various kinds of growth factors concerning the reformation of bones and PDL were manifested when the teeth were loaded mechanically.

Since it is difficult to simulate orthodontic procedure and even measure orthodontic force applied to the teeth experimentally, FEM has been widely used. Among the studies adopting FEM to simulate orthodontic procedure, one study (Zhou et al. 2016) proposed a method to apply orthodontic force on Tooth-Periodontal Ligament-Bone Complex(TPBC) by simulating installation of archwire. Using ANSYS software, the study predicted the deformation and displacement of the archwire before and after the wire installation, and the stress of the archwire induced by the deformation of archwire was obtained.

Since orthodontic treatment takes months, it is important to investigate whether time-dependent mechanical behaviors such as stress relaxation and creep exist in orthodontic devices or even teeth and bone. Regarding stress relaxation, Letaief et al.(2008) investigated the effect of relaxation mechanism of NiTi orthodontic wire and presented the stress relaxation curves. Specimens with the nominal composition of 50.8 at.% of Nickel and 49.2 at.% of Titanium were prepared in a wire shape, where a gage length was 20mm and a cross section was $0.43*0.64mm^2$. The study found that about 4.69% of stress was released after 1000 hours of loading.

Another time dependent material behavior is creep of teeth. He and Swain(2008) reported creep behaviors of teeth enamel by conducting nanoindentation tests. From the study, it was obvious that the teeth showed creep behaviors, which mechanism could be explained by the protein rich organic sheath and the thin layer between the apatite crystallites within the rods. In that reason, the study claimed that the creep behavior of enamel might be similar to those in bone. Creep behaviors of bone investigated by Ji and Gao(2004) showed that creep compliance function of bone varied from 0.25 to 1.0 as time passed.

Even though time dependent mechanical behaviors of orthodontic devices and teeth can have influence on efficiency of orthodontic treatment, there have been limited studies correlating orthodontic forces with long term material behaviors. Therefore, this study estimates stress loss of NiTi archwire in long term by including considerations of stress relaxation of wire and creep of teeth.

2. NUMERICAL METHOD

2.1 Stress loss due to relaxation of wire

In prestressed concrete theory, relaxation is a phenomenon in which the tensile stress decreases as time passes when the prestressing tendon is kept at a constant length in a stressed state. Existing design standards for prestressed concrete suggest using analytical or empirical methods to estimate stress relaxation occurring in prestressing tendon. According to Road bridge design specification(2015) and Eurocode(2004), equation for stress loss due to pure relaxation, $\triangle f_{pr}$, can be chosen depending on relaxation grade of prestressing tendon, which is categorized by the relaxation value, ρ_{1000}. The relaxation value of the NiTi archwire is found as 4.69(He and Swain 2008), which corresponds to relaxation class for hot-rolled or hardened prestressing steel bars in prestressed concrete. Therefore, the equation for estimating stress loss in prestressing steel bars(Lee 2015) can directly used for the case of NiTi archwire as presented in Eq. (1).

$$\Delta f_{pr}/day = f_{pi} * 1.98 * \rho 1000 * e^{8\mu} * \left(\frac{h}{1000}\right)^{0.75(1-\mu)} * 10^{-5}, \qquad (1)$$

where ρ1000 is a relaxation value of the NiTi archwire at the time of 1000 hours being stressed at an average temperature of 20°, h is time in hours, and μ is defined as the ratio of the initial wire stress at the time of installation to the ultimate tensile strength of the NiTi archwire, which is 1455MPa, according to the study by Fercec et al. (2014).

2.2 Stress loss due to creep of teeth

He and Swain (2008) report that the creep behavior of teeth can be considered similar to that of bone, and the creep compliance ratio of instant to long time is found as 3.0 for bone from the study by Ji and Gao (2004). Because the creep coefficient of concrete is within 2.8 to 4.0 within 28 days (Lee 2015), the equation for stress loss due to creep, Δf_{cr}, in prestressed concrete (Eq. (2)) from Lee (2015) can be modified as Eq. (3) for the estimation of stress loss in archwire due to creep of teeth.

$$\Delta f_{cr}/day = E_p \times \varepsilon_{cp} = E_p \times \varphi_{cp} \times \frac{f_{cs}}{E_c} = \frac{E_p}{E_c} \times \varphi_{cp} \times f_{cs} \qquad (2)$$

where E_p is an elastic modulus of a prestressing tendon, ε_{cp} is a creep variation of concrete, φ_{cp} is a coefficient of creep, ε_c is elasticity strain, f_{cs} is stress of concrete acting at the same position with tendon, and E_c is and elastic modulus of concrete.

$$\Delta f_{cr}/day = \frac{E_{wire}}{E_{teeth}} \times \varphi_{creep} \times f_{teeth} \qquad (3)$$

where E_{wire} and E_{teeth} is an elastic modulus of wire and teeth, φ_{creep} is a coefficient of creep, and f_{teeth} is stress of teeth at around brackets.

In the prestressed concrete design, creep coefficient is time dependent and can simply be obtained from Eq. (4) according to ACI 209 committee(1992). The equation uses t in hours and C_u as 1.6 for post tensioning method, which is similar to the method of inducing stress in archwire for orthodontic treatment.

$$C_t(t) = \frac{t^{0.6}}{10 + t^{0.6}} \times C_u \qquad (4)$$

Preceding Eqs. (1) and (3) are applied to the case of crowding model installed with NiTi archwire and brackets as shown in Fig. 1.

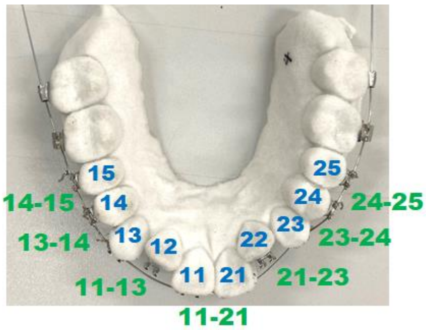

Fig.1 Crowding teeth with orthodontic devices (Numbers in green color denote wire location connecting the teeth numbered in blue color)

3. RESULTS

Table 1 lists calculated stress loss caused by stress relaxation, while table 2 are for stress losses caused by creep. Since equations for stress relaxation and creep require initial stress values on archwire and teeth, respectively, the stress losses are based on the instant stress values occurred on archwire and teeth after wire installation on the brackets.

As shown in Table 1, stress losses due to stress relaxation are varied from 0.001~11.060MPa depending on locations per day, thus 0.012~23.760MPa of stress loss can be expected after 30days of orthodontic treatment. Especially, wire locations between teeth No. 15-14 and No. 24-25 show relatively large stress loss due to relaxation, because of large initial wire stresses occurred on molar teeth area due to anchorage effect.

Stress losses due to creep are in range from 96.152~185.344MPa after 30 days of orthodontic treatment. Similar to the stress loss due to stress relaxation, stress loss due to creep does not linearly increase with time because the creep coefficient is not linearly proportion to time period. In addition, the largest stress loss occurs in the wire location between teeth No. 24 and 25, while relatively lowest stress loss is observed from the wire location between teeth No. 11 and 21. The stress loss variation depending on the location is because the Eq. (3) uses stress on tooth and each tooth is in different stress level. Stress loss values due to creep are significantly larger than those from stress relaxation, which shows that stress loss in long term is more influenced by creep behavior of teeth, than the stress relaxation of archwire.

Table 1. Stress loss due to stress relaxation (MPa)

Wire location / Time	15-14	14-13	13-11	11-21	21-23	23-24	24-25
1day	11.060	0.004	0.021	0.005	0.001	0.726	4.080
30days	23.760	0.040	0.154	0.043	0.012	2.717	10.776

Table 2. Stress loss due to creep (MPa)

Wire location / Time	15-14	14-13	13-11	11-21	21-23	23-24	24-25
1day	53.795	64.424	65.292	46.152	58.670	67.807	88.964
30days	112.075	134.219	136.027	96.152	122.232	141.267	185.344

4. CONCLUSION

In this study, long term stress loss on NiTi archwire during orthodontic treatment is estimated by adopting existing equations for calculating long term stress loss in prestressed concrete. The equations are modified to account for stress loss of NiTi archwire due to stress relaxation of archwire and creep of teeth. As results, location and time dependent long term stress losses are obtained, showing that stress loss due to creep behavior of teeth is much larger than those by stress relaxation of archwire. The suggested formulations allow estimating stress changes in archwire during orthodontic treatment so that diagnosis and treatment can be followed by effectively.

The limitation of this study is that stress loss due to change of teeth alignment is not considered, which may be overcome by investigating stress loss due to friction between the bracket and the archwire as the wire curvature changes. In addition, the formulations for estimating stress loss in long term have been validated and widely used for prestressed concrete, but not validated for the orthodontic devices experimentally.

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