Advances in Computational Design, *Vol. 6, No. 4 (2021) 319-327*
https://doi.org/10.12989/acd.2021.6.4.319

Experimental study on bolt torque–tension relationship for different washer and nut combinations

Seung-Hyeon Hwang[a], Sanghee Kim* and Keun-Hyeok Yang[b]

Department of Architectural Engineering, Kyonggi University, 154-42 Gwanggyosan-ro, Youngtong-gu, Suwon, Kyonggi-Do, 16227, Republic of Korea

(Received May 26, 2021, Revised July 31, 2021, Accepted August 22, 2021)

Abstract. This experimental study was conducted to determine nut factors based on four combinations of washers and nuts. A prestressing force was applied to a long reinforcing bar using the torque–tension method. All the sets exhibited a linear trend. The nut factors for combinations of the flat washers and hex nuts, spring washers and hex nuts, flat washers and heat-treated nuts, and flat washers and self-locking nuts were 0.228, 0.224, 0.299, and 0.397, respectively. Additionally, the relaxation of the flat washers and hex nuts in a relatively long-term period (40 days in this study) was evaluated, and eight specimens subjected to various initial prestressing forces were analyzed. The average change in prestressing force was -3.98%. It is necessary to consider prestressing force loss for relatively long-term when prestressing force is applied to a long reinforcing bar.

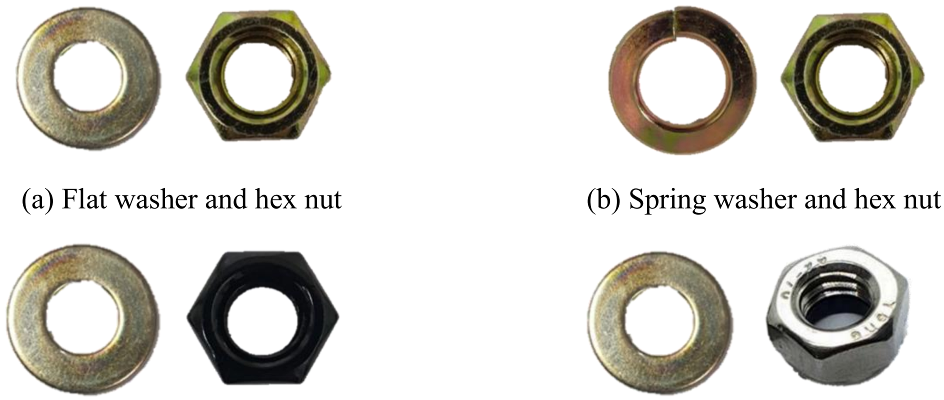
Keywords: nut factor, prestressing force, relatively long-term relaxation; torque–tension, washer and nut

1. Introduction

The prestressing method is a technique in which internal stresses are applied to a structure by introducing prestressing to a strand or bar (Kim *et al*. 2021, Lee *et al*. 2014b). Many studies have shown that structures reinforced with prestressing exhibit improved structural performance, such as shear, flexure, and energy dissipation (Kim and Kang 2019, Lee *et al*. 2015, Yang and Kang 2011). Some researchers utilized these advantages and applied the prestressing method to repair and reinforce structures (Hwang *et al*. 2020, Lee *et al*. 2014a, Yang *et al*. 2007, Yang *et al*. 2020). For example, prestressing forces have been introduced with nut fastening using a thread at the end of a long steel bar or deformed reinforcing bar. Prestressing forces are typically applied to steel bars or deformed reinforcing bars using the torque control method, which provides tensile forces through the torque generated by nut tightening. Thus, it is possible to easily introduce prestressing forces. Furthermore, it is necessary to evaluate the relaxation after the initial introduction of prestress. For typical bolt–nut combinations, the torque force (T) can be obtained by multiplying the diameter (d_b), tensile force (F), and nut factor (k), where the conventional value of the nut

*Corresponding author, Assistant Professor, E-mail: sanghee0714@kyonggi.ac.kr
[a]Ph.D. Candidate, E-mail: hyongha89@gmail.com
[b]Ph.D. Professor, E-mail: yangkh@kgu.ac.kr

http://www.techno-press.org/?journal=acd&subpage=7 ISSN: 2383-8477 (Print), 2466-0523 (Online)



(a) Flat washer and hex nut (b) Spring washer and hex nut

(c) Flat washer and heat-treated hex nut (d) Flat washer and self-locking nut

Fig. 1 Sets of washer and nut

factor ranges from 0.15 to 0.2 (Croccolo *et al*. 2011). However, the torque control method yields different torque values based on the type of nut, thread, and material.

The type of prestressing force loss generated by the bolt–nut combination can be divided into immediate loss and relatively long-term loss induced by prestressing steel relaxation. Immediate losses are caused by a slip in the anchorages immediately after jacking and the friction between parts. This loss type is generally compensated for through overstressing. Long-term losses are caused by the relaxation of prestressing steel, in which the prestressing force gradually decreases with the constant strain of the prestressing steel in long term (Ye *et al*. 2020). Therefore, it is necessary to evaluate the prestressing losses generated by the prestressing bar relaxation based on the relatively long-term behavior of the bolt–nut combination.

There is a lack of research on whether the conventional k-value may be applied to long steel bars and whether relatively long-term tensile force loss occurs. In this study, an attempt was made to evaluate whether tensile force is introduced to the long deformed reinforcing bar when a torque force is applied with a nut at one end of the bar. Based on various combinations of nuts and washers, the nut factor was determined. In addition, tests were conducted to confirm whether there was a loss of prestressing force in the relatively long term.

2. Experimental program

2.1 Test method for correlation between torque and tension

The main parameter of the torque experiment was the combination of the nut and washer, and four combination sets were prepared. These combinations were a flat washer and a hex nut (A-set), a spring washer and a hex nut (B-set), a flat washer and a heat-treated hex nut (C-set), and a flat washer and a self-locking nut (D-set) (Fig. 1). The A-set has been widely employed, and the combined spring washer and self-locking nut were developed to suppress the loosening of the torque force. The heat-treated nut exhibits increased nut strength. All nuts used in this study of the M16 type.

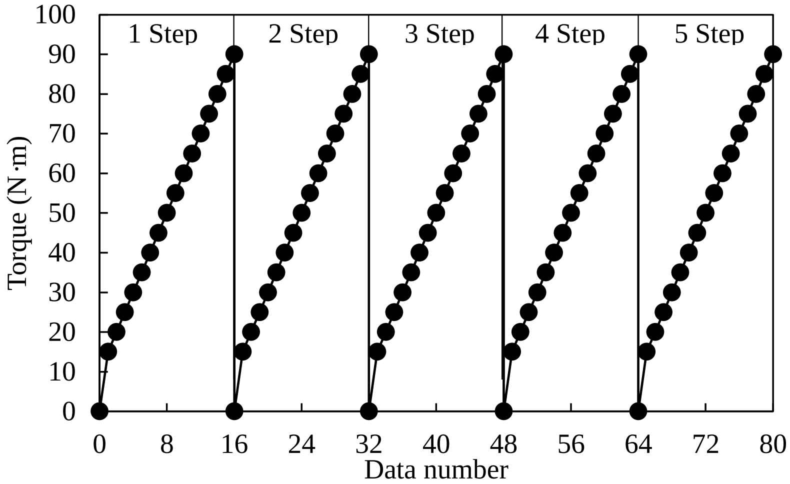
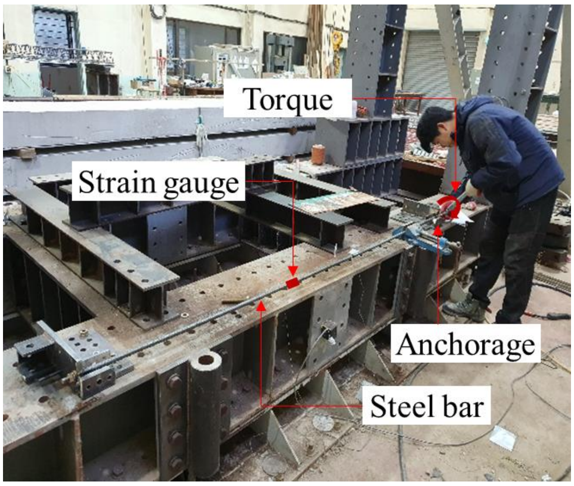
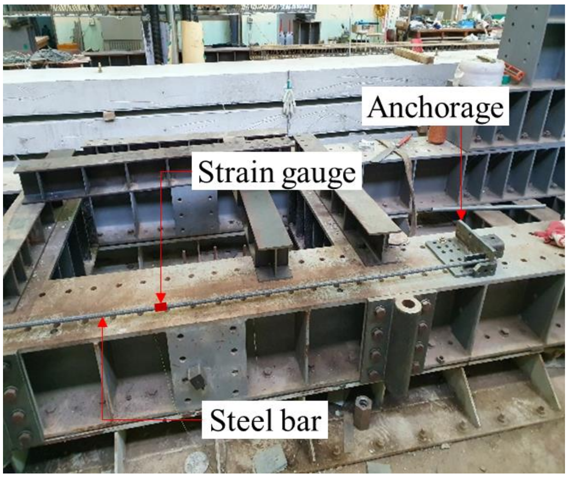


Fig. 2 Loading plan



(a) Torque test



(b) Relaxation test

Fig. 3 Photographs showing experimental tests

The measured yield strength ($f_{y,meas}$) of the deformed reinforcing bar was approximately 628 MPa. The nominal diameter of the deformed reinforcing bar was 16 mm, and the diameter of the thread end obtained using a cutting method was 14 mm. Both ends of the reinforcing bar were fixed using a nut-tightening method corresponding to each variable, and an initial torque force of 15 N-m was applied to the deformed reinforcing bar. The torque force was successively increased in steps of 5 N-m, and the maximum applied force was 90 N-m (Fig. 2). Subsequently, the load was reduced to zero, and the loading process was repeated five times. The strain values were recorded every 5 N-m. The torque force was applied only to one end and measured using a torque wrench (Fig. 3(a)). A strain gauge was installed at the center of the bar to determine the tensile force (Fig. 4). The tensile force corresponding to the strain value was founded with a stress-strain curve (Fig. 5).

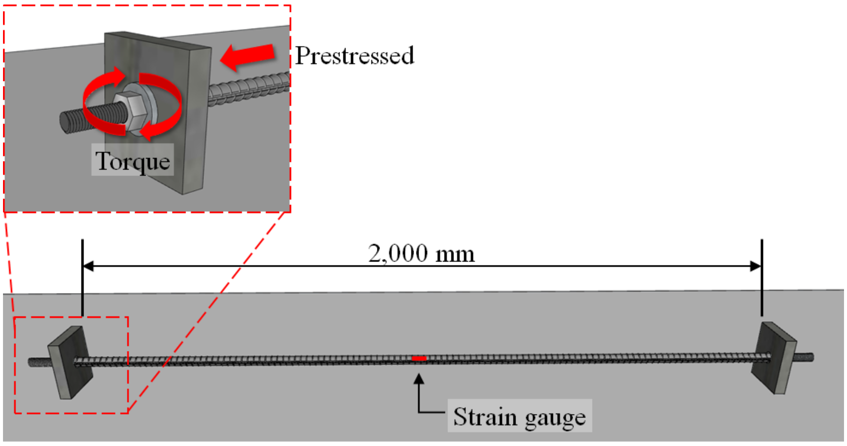


Fig. 4 Schematic of long reinforcing bar with set of washer and nut

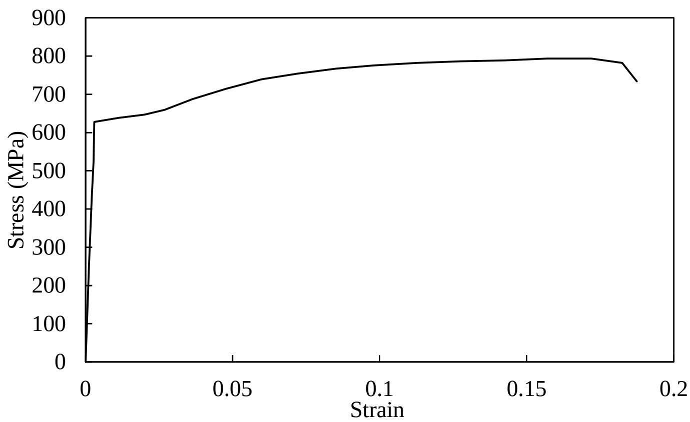


Fig. 5 Measured stress-strain curve of reinforcing bar

2.2 Test method to evaluate relatively long-term relaxation

It is necessary to evaluate the relaxation of the torque force applied to the long deformed reinforcing bar to ensure that there is no loss of prestressing force stability in the relatively long term. For the relatively long-term relaxation tests, a set of flat washers and hex nuts was employed because this combination is widely used. Additionally, a low nut factor value indicates a low frictional force, signifying a high probability of prestressing force loss in the relatively long term. Therefore, experiments were performed only for the flat washer and hex nut combination in this study.

Eight specimens with various initial prestressing force levels (the ratio of initial prestressing force to measured yield strength) of 0.224, 0.226, 0.194, 0.165, 0.302, 0.258, 0.284, and 0.270 were used to record the variations in the prestressing force. Additionally, the steel bar`s strain without prestressing force was measured during the relaxation tests to determine the change in steel bar strain with temperature (Fig. 2(b)). The variation in strain at the center of the deformed reinforcing bar was measured for 40 days in intervals of 2 min.

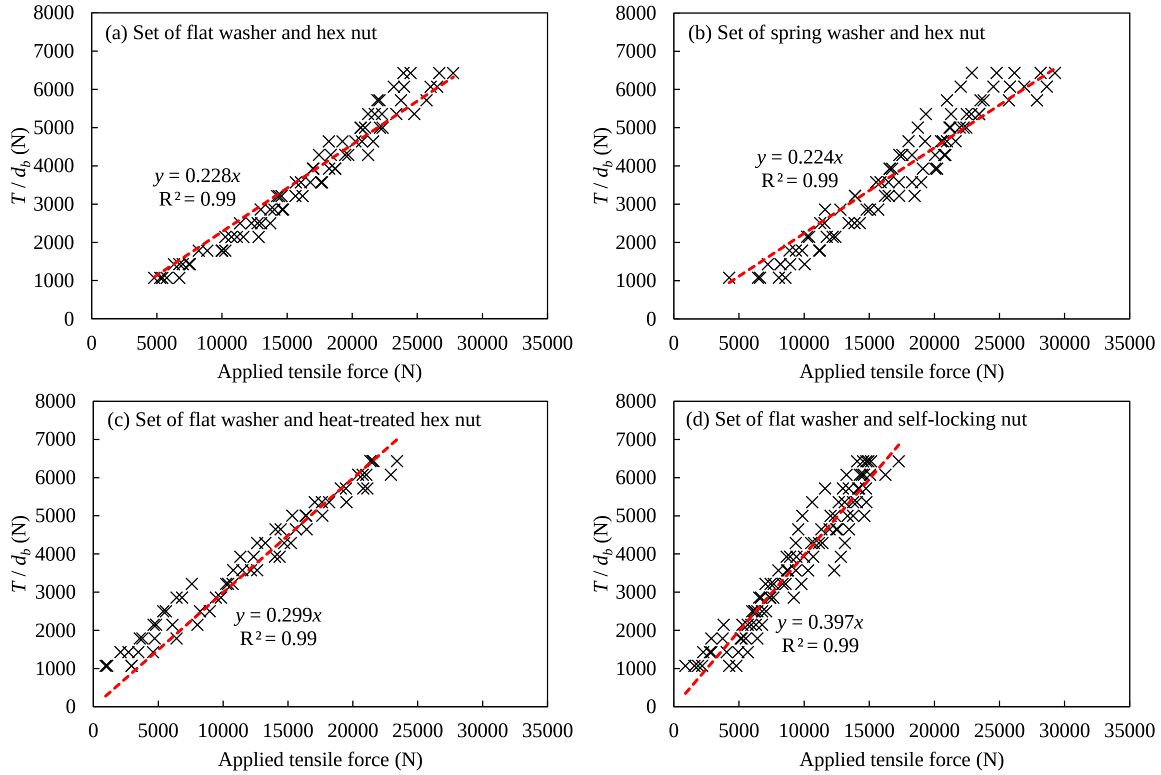


Fig. 6 Relationship between applied tensile force and T/db for each washer–nut set

Table 1 Nut factors of different nut and washer sets

Test set	Set of flat washer and hex nut	Set of spring washer and hex nut	Set of flat washer and heat-treated hex nut	Set of flat washer and self-locking nut
Nut factor (*k*)	0.228	0.224	0.299	0.397

3. Experimental results

3.1 Torque–tension relationship

Fig. 6 shows the torque–tension relationship for each set of washers and nuts. The X-axis in Fig. 6 displays the corresponding applied force (F), and the Y-axis shows the torque force (T) divided by the thread diameter (d_b), where F is obtained from the relationship between the measured tensile and stress as shown in Fig. 5. The torque force can be calculated as the product of the tensile force (F), nut factor (k), and thread rod diameter (d_b), as expressed in Eq. (1), where k depends on the type of bolt, nut, and thread. All sets exhibited a linear relationship between F and T/d_b until the completion of the experimental tests. Thus, a nut factor was obtained to determine the slope as a constant (a) in the linear equation form, $y = ax$.

$$T = kFd_b \tag{1}$$

The nut factors for the flat washer and hex nut (A-set), spring washer and hex nut (B-set), flat

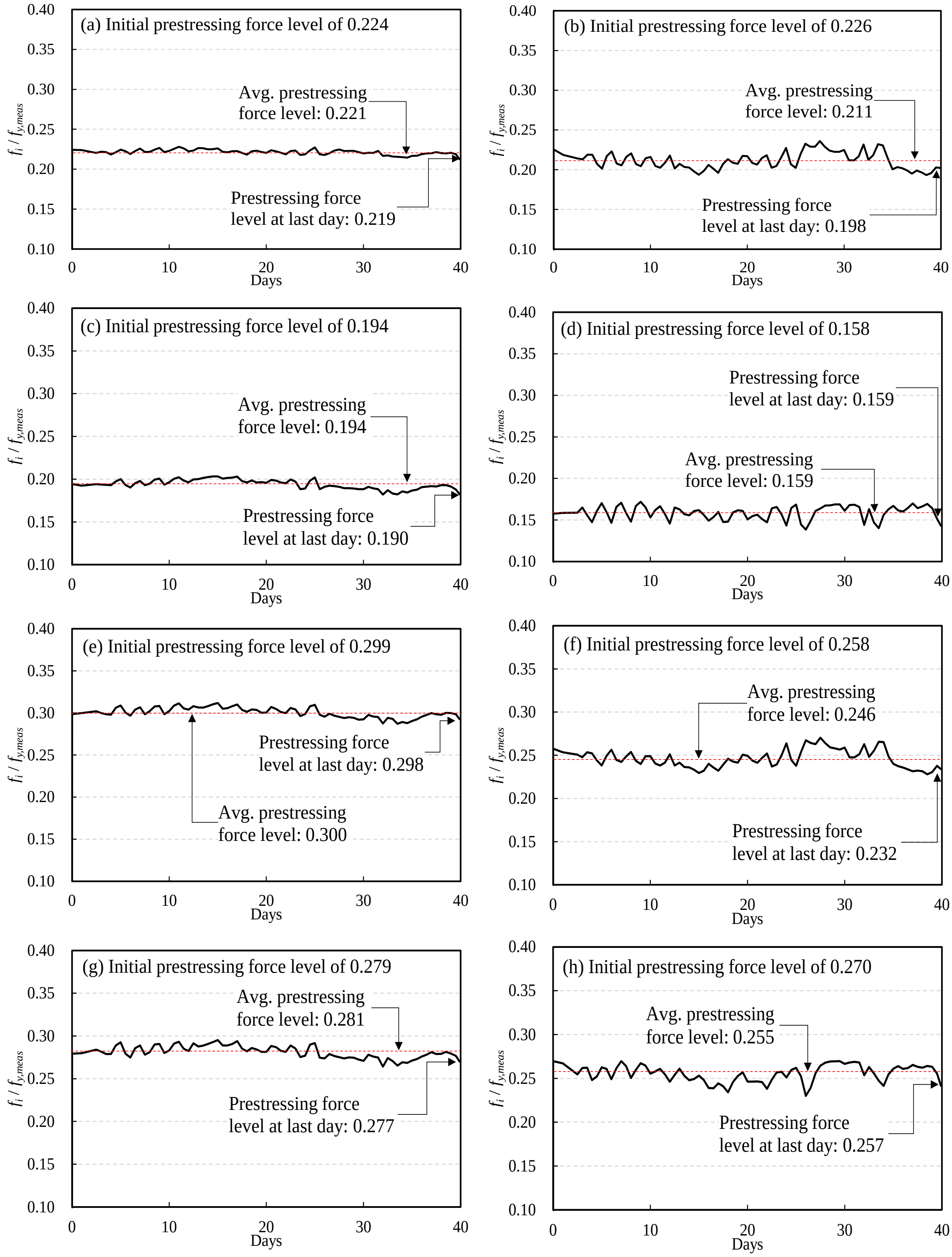


Fig. 7 Relaxation test results (set of flat washer and hex nut)

Table 2 Measured prestressing force levels

Specimen	A	B	C	D	E	F	G	H
σ_{ini}	0.224	0.226	0.194	0.158	0.299	0.258	0.279	0.270
σ_{2nd}	0.224	0.218	0.192	0.159	0.300	0.254	0.280	0.267
Loss (%)	−0.18	−3.13	−0.98	0.70	0.37	−1.56	0.18	−0.93
σ_{avg}	0.221	0.211	0.194	0.159	0.300	0.246	0.281	0.255
Loss (%)	−1.36	−6.29	−0.21	0.77	0.59	−4.51	0.68	−5.30
σ_{last}	0.218	0.198	0.190	0.159	0.298	0.232	0.277	0.257
Loss (%)	−2.69	−12.14	−2.51	0.90	−0.34	−9.80	−0.71	−4.57

Note: σ_{ini} is the prestressing force level when the initial force is applied; σ_{2nd} is the prestressing force level on the 2nd day; σ_{avg} is the average prestressing force level from the 2nd to the 40th day; σ_{last} is the prestressing force level for the last three days (38th to 40th day).

washer and heat-treated hex nut (C-set), and flat washer and self-locking nut (D-set) were 0.228, 0.224, 0.299, and 0.397, respectively (Table 1). The *k* values for the A-set were slightly higher than the typical value (0.2). When a bolt and a nut are fastened by torque, there is underhead friction between the bolt-head and plate, tread friction between the nut and thread, and tension of the bar, only 10% of torque induces tension to the bar (Tronci 2017). Under the test conditions, it was assumed that the loss of torque decreased because no friction was generated between the bolt-head and the plate. Thus, the nut factor of the A-set was slightly higher than the typical range of 0.15–0.2 for the flat washer and hex nut set. The nut factor of the B-set was similar to that of the A-set, and the C-set and D-set values were 1.31 and 1.74 times higher, respectively, than the A-set value. The slope of the flat washer and self-locking nut combination was higher than that of the flat washer and hex nut combination because of the higher frictional force between the bolt and the self-locking nut for introducing prestress (Yang *et al*. 2021). This difference occurred because the self-locking nut exhibited greater frictional force and better anti-loosening performance than the other nuts.

3.2 Relaxation test results

Fig. 7 depicts the strain history at the center of the long bar, considering the variation in the strain caused by temperature changes. Table 2 lists the prestressing force level (σ) at the time of stressing (σ_{ini}), on the 2nd day (σ_{2nd}), the average value (σ_{avg}, from two to 40 days), and the last three days (σ_{last}). f_i and $f_{y,meas}$ are the initial prestress and the measured yield strength of the reinforcing bar, respectively. Each loss value was calculated by subtracting σ from σ_{ini} and dividing the difference by σ_{ini} (i.e., $100 \times (\sigma_{ini} - \sigma)/\sigma_{ini}$). After 24 hours, the variation in the prestressing force level ranged from +0.7% to –5.3%, and the average prestress loss of all specimens was –0.69%. For the specimens D, E, and H, the prestressing force level increased slightly; it was assumed that these specimens were influenced more by temperature than the specimen installed to reflect the strain variation caused by temperature.

The changes in the σ_{avg} values of all specimens ranged from +0.77% to –6.29%, with an average value of –1.95%. The σ values of the specimens B, H, and F decreased by more than 5%, and specimen B lost 6.29% of its σ_{ini} value, which corresponded to the maximum loss. For the prestressing levels of the specimens during the last three days, the variations ranged from +0.9% to –12.14%, and the average loss value was –3.98%. For specimens B and F, the loss in the prestressing force levels were 12.14% and –9.8%, respectively. The loss was significant on the 35th day, and the loss was not recovered until the fifth day.

4. Conclusions

In this study, experimental tests were performed to determine nut factors based on various sets of washers and nuts and when prestressing force is applied to a long steel bar using the torque control method. In addition, when a flat washer and a hex nut were fastened to the thread of the long steel bar, it was investigated whether a relatively long-term loss of tension occurred. The nut factors for the flat washer and hex nut, spring washer and hex nut, flat washer and heat-treated nut, and flat washer and self-locking nut were 0.228, 0.224, 0.299, and 0.397, respectively. The flat washer and hex nut combination introduced prestressing forces on the long steel bar more easily than the other combinations. For the flat washer and hex nut set, the initial change in prestressing force on the second day ranged from +0.7% to –5.3%, and seven specimens lost their prestressing forces. The prestressing force loss in the last three days ranged between +0.9% and –12.14%, and the average loss was –3.98%. It was confirmed that the relaxation of the reinforcing bars with the prestressing force showed less than approximately –12% variation from the initially applied prestress. Therefore, the prestressing force could be stably maintained in terms of relatively long-term behavior, although a slight loss of prestressing force was observed.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (No. 2015R1A5A1037548) and by the Korea Agency for Infrastructure Technology Advancement funded by the Ministry of Land, Infrastructure and Transport of the Korean government (No. 21TMIP-C158687-02).

References

Croccolo, D., Agostinis, M.D. and Vincenzi, N. (2001), “Failure analysis of bolted joints: Effect of friction coefficients in torque-preloading relationship”, *Eng. Fail. Anal.*, **18**(1), 364-373. https://doi.org/10.1016/j.engfailanal.2010.09.015.

Hwang, S.H., Kim, S. and Yang, K.H. (2020), “In-plane seismic performance of masonry wall retrofitted with prestressed steel-bar truss”, *Earthq. Struct.*, **19**(6), 459-469. http://doi.org/10.12989/eas.2020.19.6.459.

Kim, K. and Kang, T.H.K. (2019), “Experiments on continuous unbonded post-tensioned beams with 2400 MPa (350 ksi) strands”, *ACI Struct. J.*, **116**(5), 125-136. https://doi.org/10.14359/51716758.

Kim, S., Kang, T.H.K., Jung, D. and LaFave, J.M. (2021), “Seismic behavior of precast and post-tensioned exterior connections with ductile headed rods”, *ACI Struct. J.*, **118**(1), 87-100. https://doi.org/10.14359/51728179.

Lee, S.H., Lee, H.D., Shin, K.J. and Kang, T.H.K. (2014a), “Shear strengthening of continuous concrete beams using externally prestressed steel bars", *PCI J.*, **59**(4), 77-92. https://doi.org/10.15554/pcij.09012014.77.92.

Lee, S.H., Shin, K.J. and Kang, T.H.K. (2014b), "Non-iterative moment capacity equation for reinforced concrete beams with external post-tensioning", *ACI Struct. J.*, **111**(5), 1111-1121. https://doi.org/10.14359/51686815.

Lee, S.H., Shin, K.J. and Kang, T.H.K. (2015), "Flexural strengthening of continuous concrete beams using external prestressed steel bars", *PCI J.*, **60**(1), 68-86. https://doi.org/10.15554/pcij60.1-01.

Tronci, G. (2017), *Frictional Behavior of Coated Self-Locking Aerospace Fasteners*, Ph.D. Dissertation, University of Sheffield, U.K.

Yang, B., Sun, Q., Lin, Q., Wang, L., Zhang, X. and Ma, Y. (2021), "Influence mechanism of bolted joint with geometric irregularity bearing surface on anti-loosening performance", *Int. J. Press. Vessel Piping*, **191**, 1-15. https://doi.org/10.1016/j.ijpvp.2021.104364.

Yang, K.H. and Kang, T.H.K. (2011), "Equivalent strain distribution factor for unbonded tendon stress at ultimate", *ACI Struct. J.*, **108**(2), 217-226.

Yang, K.H., Mun, J.H. and Hwang, S.H. (2020), "Cyclic shear behavior of masonry walls strengthened with prestressed steel bar and glass fiber grids", *Compos. Struct.*, **238**, 1-12. https://doi.org/10.1016/j.compstruct.2020.111961.

Yang, K.H., Sim J.I. and Byun, H.Y. (2007), "Shear capacity of reinforced concrete continuous T-beams externally strengthened with wire rope units", *J. Korea Concrete Inst.*, **19**(6), 773-783. https://doi.org/10.4334/JKCI.2007.19.6.773.

Ye, C., Butler, L.J., Elshafie, M., Z.E.B. and Middleton, C.R. (2020), "Evaluating prestress losses in a prestressed concrete girder railway bridge using distributed and discrete fibre optic sensors", *Construct. Build. Mater.*, **247**, 1-18. https://doi.org/10.1016/j.conbuildmat.2020.118518.

TK