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FINITE ELEMENT ANALYSIS OF A STEEL POST INSERTED IN POLYMER CYLINDER UNDER PULL-OUT AND TORQUE LOADINGS

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ABSTRACT

Posts are used in various implant designs to contribute to the short- and long- term fixation stability of artificial joints. This study was undertaken to provide further information on the effect of torque loading on the pull-out response of steel post inserted in polymer material. 3 D finite element analysis, using ABAQUS program, were developed on metallic post inserted in polymer cylinder with initial interference under pull-out, torque and combined torque/pull-out loadings. For the polymer cylinder materials we have considered a High Density Polyethylene (HDPE) cylinder with well known mechanical and tribological properties. The predicted ultimate pull-out force undergoes non linear decrease as the applied torque increases. The important decreasing rate was observed when the applied torque exceeded 25 % of the ultimate torque. The radial and shear stresses are significantly changed under pull-out and the combined pull-out/torque forces. The finite element prediction corroborate with our recently experimental results developed on HDPE material. The predicted results of post inserted in polyethylene materials can, therefore, demonstrate the effect of torque loading on the pull-out force.

KEY WORDS

Finite element method, Interface, Load transfer, Friction, Pull-out, Torque, Combined pull-out/torque.

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INTRODUCTION

The contribution of fiber-matrix interface, in the mechanical performance of fiber-reinforced composites, is mainly related to its potential for transferring mechanical loads from matrix to fiber during loading [1]. Such load transfer is of great importance in dentistry when a post is used for fixing a ceramic crown on the tooth [2, 3]. Posts are also used in various implant designs to contribute to the short- and long- term fixation stability of artificial joints. The long-term performance of joint replacement systems depends, in part, on the short-term stability of the fixation systems attaching the prosthesis to the host bone [4-8]. In a cementless implant, the friction at the bone-implant interface plays an important role in the transfer of shear forces and hence in the stability of the system, particularly in the immediate post-operative period when no bony ingrowth has yet occurred. To characterise the mechanical behaviour of the cement-implant interface, Mann et al. [9] used push-through test in the simpler case of metallic stem surrounded by cement column. Since the metallic stem and the cement have no chemical adhesion, the authors suggest that the Coulomb friction at the interface and the residual stress normal to the interface are the properties required to describe load transfer between stem and cement. Shirazi-Adl et al. [10] studied the pull-out response of metallic posts, with different surface roughness, inserted in both bone and polyurethane material with initial interference. For the same test conditions, the maximum pull-out force of the smooth surfaced post was much greater than that of the porous coated post.The pull-out force was found to also depend on the bone arrangement and boundary conditions. Dammak et al. [11] studied the effect of horizontal shear loading on the pull-out strength of posts inserted in polyurethane material. They concluded the axial pull-out force of smooth posts was not affected significantly by increasing the shear loading. However, the axial pull-out force was affected for porous-coated posts.

The tibial component with central post can be submitted to the effect of torque which can probably affect the pull-out strength. Then, the influence of torque on the fixation response of post inserted in bone should be investigated. To provide further information on the contribution of post fixation to the initial stability, this work aims to analyze the effect of applied torque to the load transfer at the post fixation interface under pull-out loading. Finite element analysis, using ABAQUS program, were developed on metallic post inserted in polymer cylinder with initial interference under pull-out, torque and combined torque/pull-out loadings. High Density Polyethylene (HDPE) cylinder with well known mechanical and tribological properties was considered. Finite element results for post inserted in HDPE material were compared and analyzed with our experimental work. The predicted results of post inserted in HDPE material can, therefore, demonstrate the effect of torque loading on the pull-out response. This finding can be useful in the improvement of fixation stability in various implant designs under combined loading.

MATERIALS AND METHODS

Finite element models for pull-out and torque loadings of smooth-surfaced posts inserted in HDPE cylinders are developed and analyzed using ABAQUS FE program (ABAQUS, Ver 6.4, Hibbit, Karlsson and Sorenso, Inc., 2003). Finite element model was based on the previously experimental work [12]. The diameter of the post is D=10.4 mm, the insertion length is L =15 mm and the drill size is DS = 10 mm. The

HDPE cylinders are 50 mm in diameter and 15 mm in height. The effective interference at the metal/HDPE interface is 0.2.The elastic moduli of the metal post and the polyethylene materials are 220 000 MPa and 974 MPa, respectively, with a Poisson ratio of 0.3 for metal material and 0.35 for polyethylene material. The friction coefficient at the polyurethane-metal interface is 0.07. The finite element grid used for pull-out loading, torque loading and combined pull-out/torque loading of post inserted in HDPE cylinder is shown in Fig.1. A total of 12150 eight node elements, 3600 six node elements and a total of 16331 nodal points were used. For boundary condition, the lateral surface of HDPE cylinder is firmly fixed. For pull-out loading, the external axial force is applied uniformly on the top of the post. In the cases of torque and combined pull-out/torque loadings, the torque is applied at the upper surface and along the axis of post. The applied load is increased step by step and the nonlinear response is computed. In this manner, the interface stresses are determined for every load step until the applied load reaches the ultimate pull-out force of the post, at which step no additional shear stress can be carried along the interface.

RESULTS AND DISCUSSION

Pull-out and Torque Loadings Analysis

The predicted pull-out and torque responses of a metal post inserted in HDPE are shown in Fig. 2 and Fig. 3 respectively. The torque increases with the rotation angle in a linear manner until it reaches a maximum value. Both loading conditions provide the same feature for the evolution of the pull-out force and the torque with the axial displacement and the rotation angle respectively.

Combined Pull-Out/Torque Loading Analysis

For the combined pull-out and torque loadings condition, the predicted load-displacement responses of a metal post inserted in HDPE cylinder for different constant applied torques are presented in Fig. 4. The initial contact stiffness between post and HDPE is not affected by the constant applied torque value. However the ultimate pull-out force decreases as the constant applied torque increases. Fig. 5 show finite element model results for torque versus rotation angle for metal post inserted in HDPE cylinder under different constant applied axial forces. For these loading conditions it appears that the ultimate torque decreases as the constant applied axial force increases while the initial contact stiffness remain constant.

Our recently experimental ultimate pull-out force versus applied torque curve for metal post inserted in HDPE cylinder is shown in Figure 6 [12]. In the same figure, predicted results from our finite element model are also presented for two loading process. The first loading process consist of applying constant torque before pull-out, while the second loading process consist of applying constant axial force before torque loading. It can be seen from the finite element results that the ultimate axial force/applied torque does not depend on the loading process. The ultimate pull-out force show a non linear decrease as the applied torque increases. An important decreasing rate of the ultimate pull-out force was observed when the applied torque exceeded 25 % of the ultimate torque. This behavior can be attributed to the change of the shear stress direction at the post/HDPE interface under constant applied torque condition. From the result of Fig. 6 it can be seen that the finite element model yield similar trends as the experimental measurement.Ultimate axial displacement as a function of the constant applied torque from our finite element model results are shown in Fig. 7. From this result it appear that the ultimate axial displacement/applied torque does not depend on the loading process.The ultimate axial displacement present also a non linear decrease as the applied torque increases. The decreasing rate of the ultimate pull-out displacement becomes important when the applied torque exceeded 25 % of the ultimate torque. Predicted evolution of the rotation angle with the pull-out force under different constant applied torques for metal post inserted in HDPE cylinder is presented in Fig. 8. Analysis of these results indicates that the rotation angle undergoes a constant level at the beginning after which rapid increase happens when the pull-out force approaches the ultimate pull-out force. Similar trends have been observed for the evolution of axial displacement of post with torque under different constant applied axial forces (Fig. 9). In fact the axial displacement which is being in a constant level at the beginning increases rapidly when approaching the ultimate torque.

Interfacial Stresses Analysis

Predicted radial stress σ_{11} profiles along the post/HDPE interface, for different loading conditions, are shown in Fig. 10. For the unloaded condition, i.e. interference only, the radial stress profile is approximately uniform along the interface with a mean value of -24MPa. This stress profile is not affected by the torque loading. However a significant distortion of the σ_{11} profile occurs for the pull-out and the combined pull-out/torque loading conditions. When the pull-out force approaches the ultimate pull-out force, the σ_{11} stress presents a minimum value for the upper interface edge and a maximum value for the lower interface edge.

Shear stress τ_{12} profiles along the post/HDPE interface, for different loading conditions, are shown in Fig. 11. For the unloaded condition, i.e. interference only, the τ_{12} stress present dissymmetrical repartition with regard to the interface middle. This stress profile is not affected by the torque loading. However a significant change of the τ_{12} profile occurs for the pull-out and the combined pull-out/torque loading conditions. When the pull-out force approaches the ultimate pull-out force, the τ_{12} stress profile becomes approximately uniform along the interface with a mean value of -1.5MPa.

Shear stress τ_{13} profiles along the post/HDPE interface, for different loading conditions, are shown in Fig. 12. The interference at the post/HDPE does not induce shear stress τ_{13} and this stress state is not affected by the pull-out loading. However the torque and the combined pull-out/torque loadings induce shear stress τ_{13} at the interface. The τ_{13} stress profile is approximately uniform and it has a mean value of 1.5MPa when the torque approaches the ultimate torque.

CONCLUSIONS

The objective of the present work was to investigate the effect of torque loading on the pull-out behavior of metal post inserted in HDPE cylinders with well known mechanical and tribological properties. Finite element models for pull-out, torque and combined torque/pull-out loadings were developed to analyse the load transfer for our experimental results. Some of the salient findings are as follows:

- The ultimate pull-out force and displacement undergoes non linear decreases as the applied torque increases. The important decreasing rate was observed when the applied torque exceeded 25 % of the ultimate torque.
- For the pull-out loading under constant applied torque, rapid increase of the rotation angle happens when the pull-out force approaches the ultimate pull-out force.
- For the torque loading under constant applied axial force, rapid increase of the axial displacement happens when the torque approaches the ultimate torque.
- Finite element results yield similar trends as measured results.
- Pull-out loading induces interfacial shear stress τ_{12} with an approximately uniform profile of -1.5 MPa when the pull-out force approaches the ultimate pull-out force.
- Torque loading induces interfacial shear stress τ_{13} with an approximately uniform profile of 1.5 MPa when the torque approaches the ultimate torque.
- The predicted results of post inserted in HDPE material can, therefore, demonstrate the effect of torque loading on the post-operative short term fixation stability of various implant designs.

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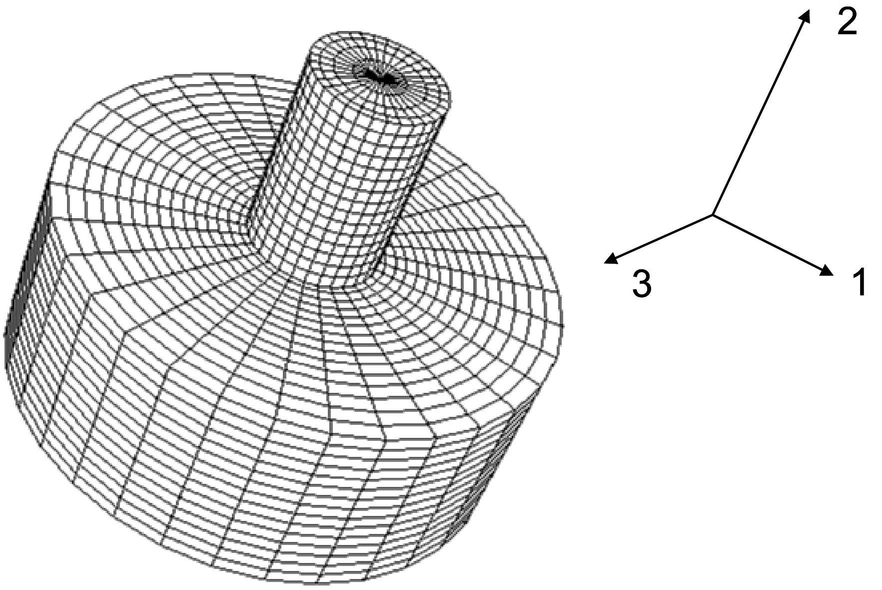

Fig. 1: Finite element mesh of post inserted in HDPE cylinder.

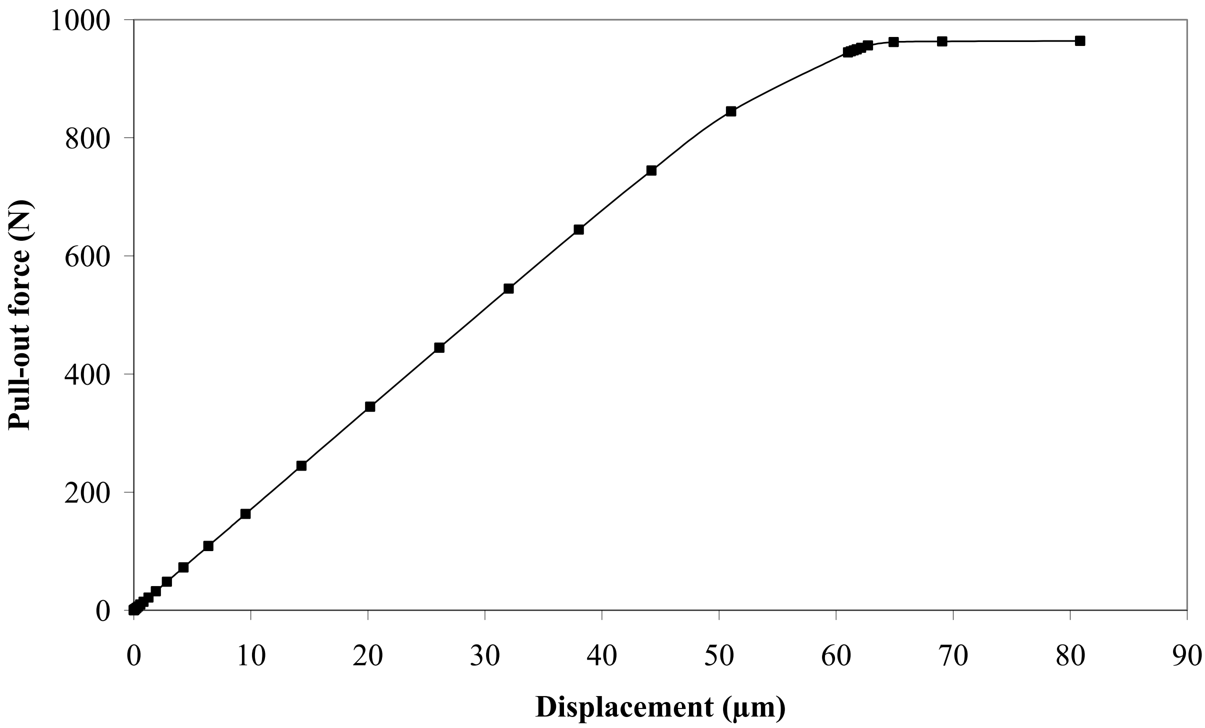

Fig. 2: Finite element pull-out force versus displacement for metal post inserted in HDPE cylinder.

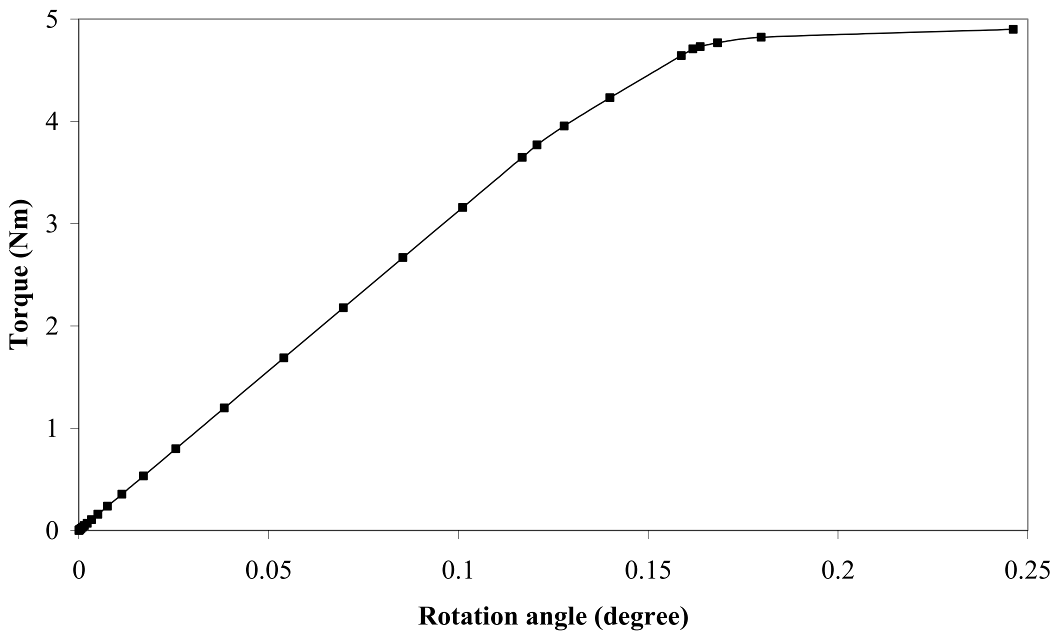

Figure 3: Finite element torque-rotation curves for metal post inserted in HDPE cylinder.

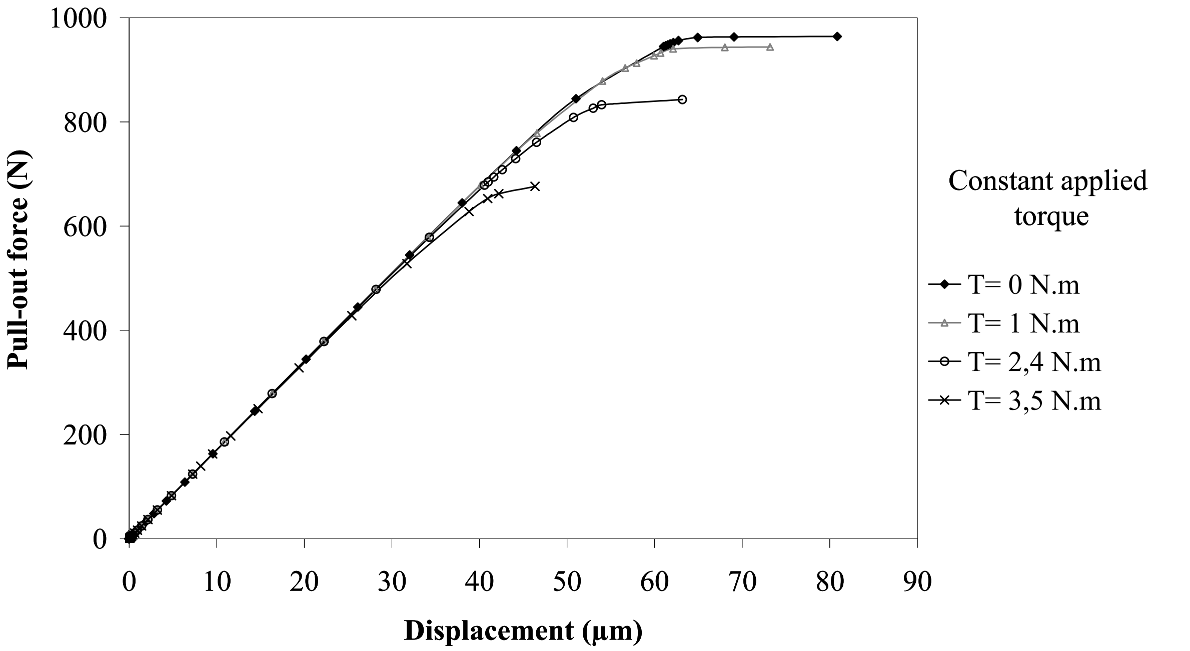

Fig. 4: Finite element pull-out force versus axial displacement curves for metal post inserted in HDPE cylinder under different constant applied torques.

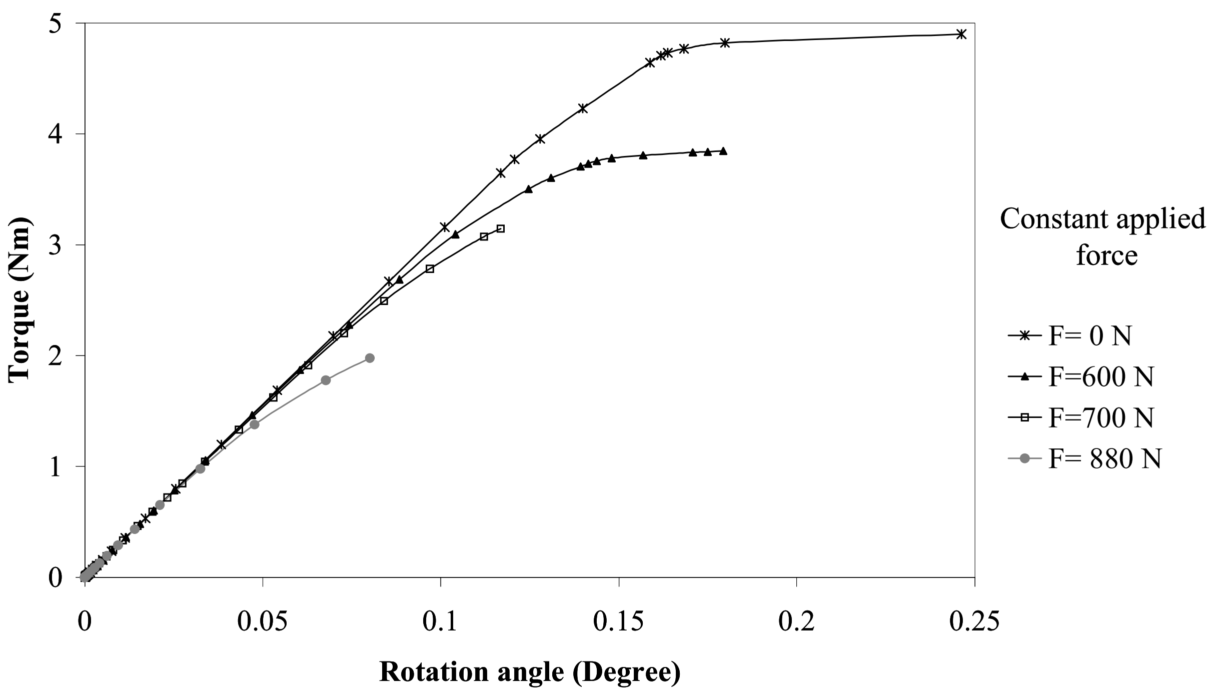

Fig. 5: Finite element torque versus rotation angle curves for metal post inserted in HDPE cylinder under different constant applied axial forces.

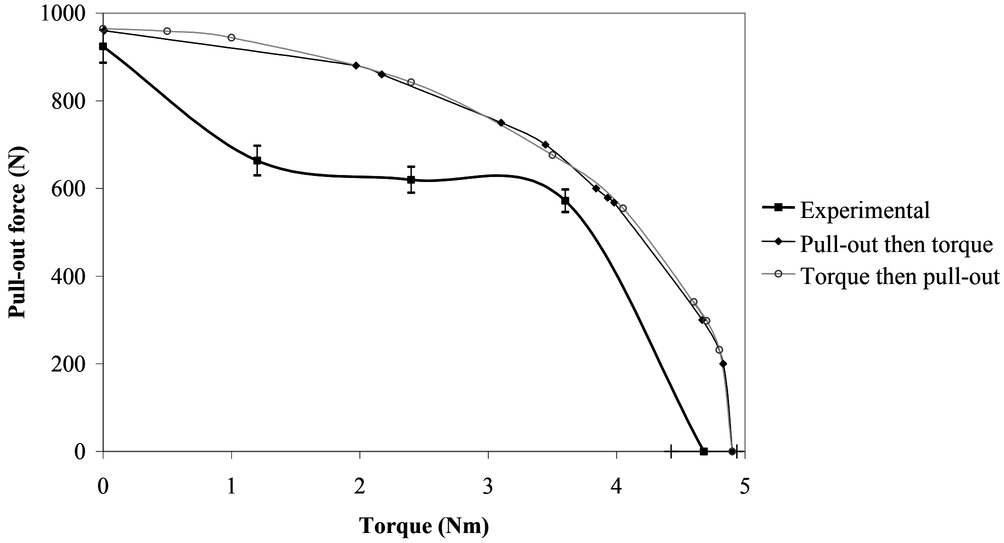

Fig. 6: Predicted and experimental pull-out force versus torque for metal post inserted in HDPE cylinder.

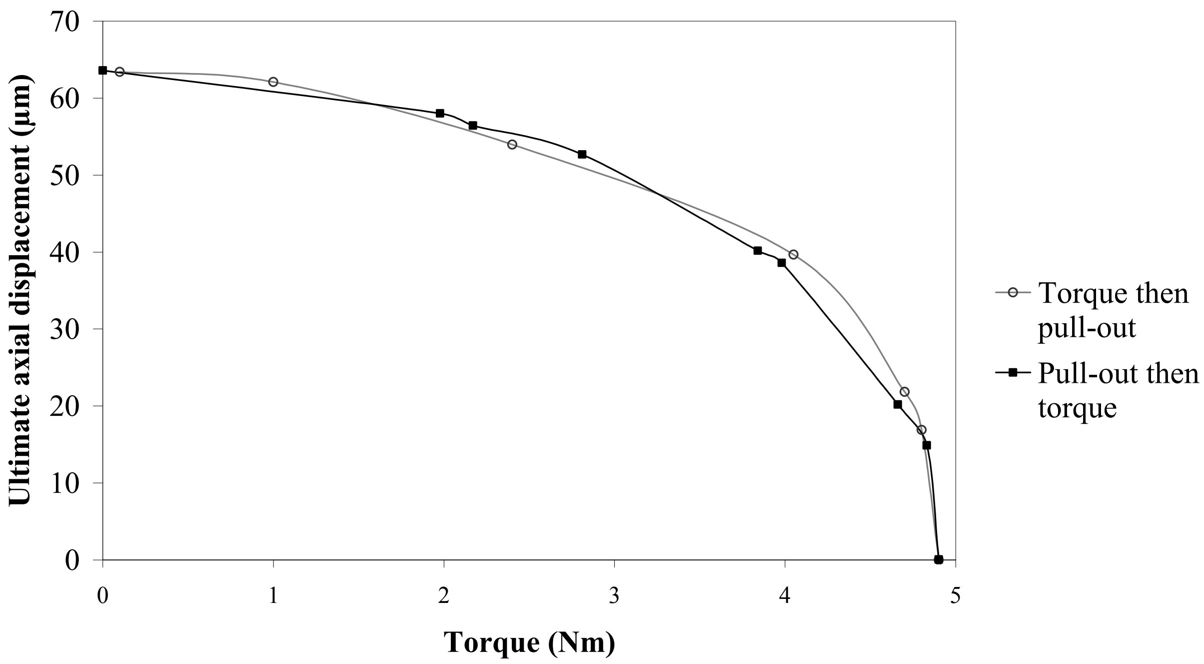

Fig. 7: Finite element ultimate axial displacement versus applied torque curves for metal post inserted in HDPE cylinder.

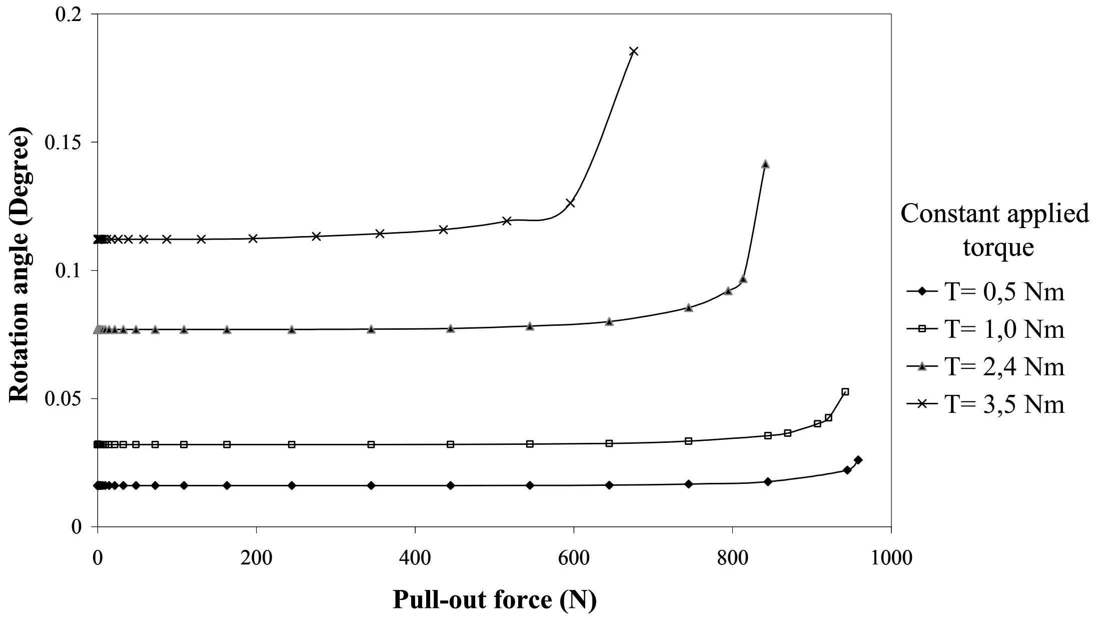

Fig. 8: Finite element rotation angle versus pull-out force curves for metal post inserted in HDPE cylinder under different applied torques.

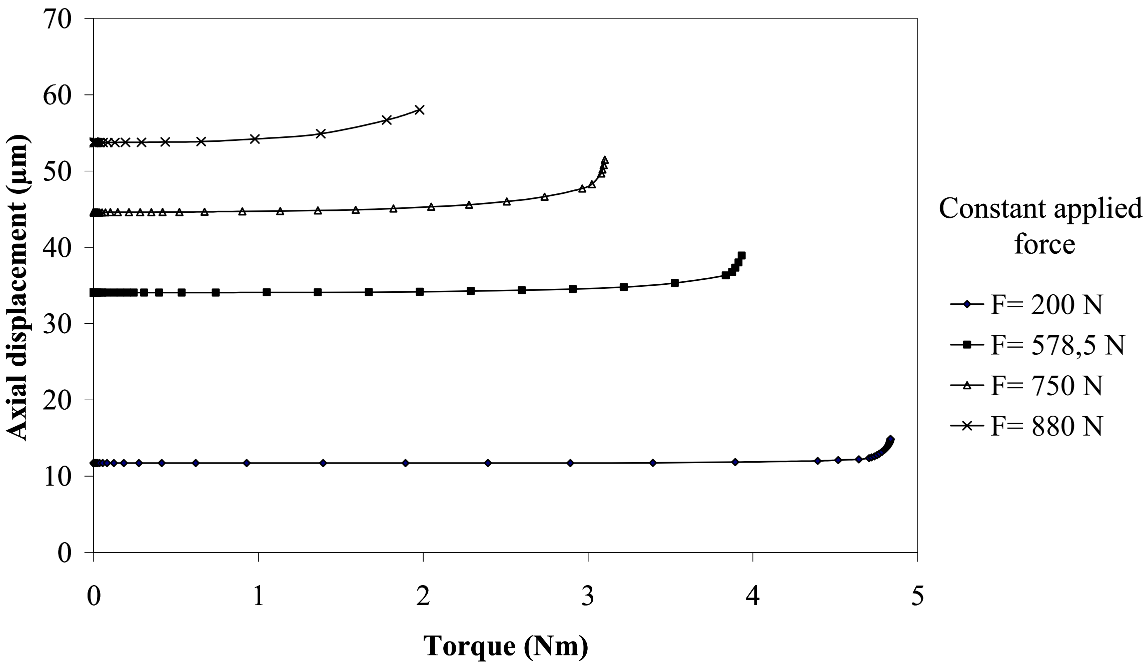

Fig. 9: Finite element axial displacement versus torque curves for metal post inserted in HDPE cylinder under different constant applied axial forces.

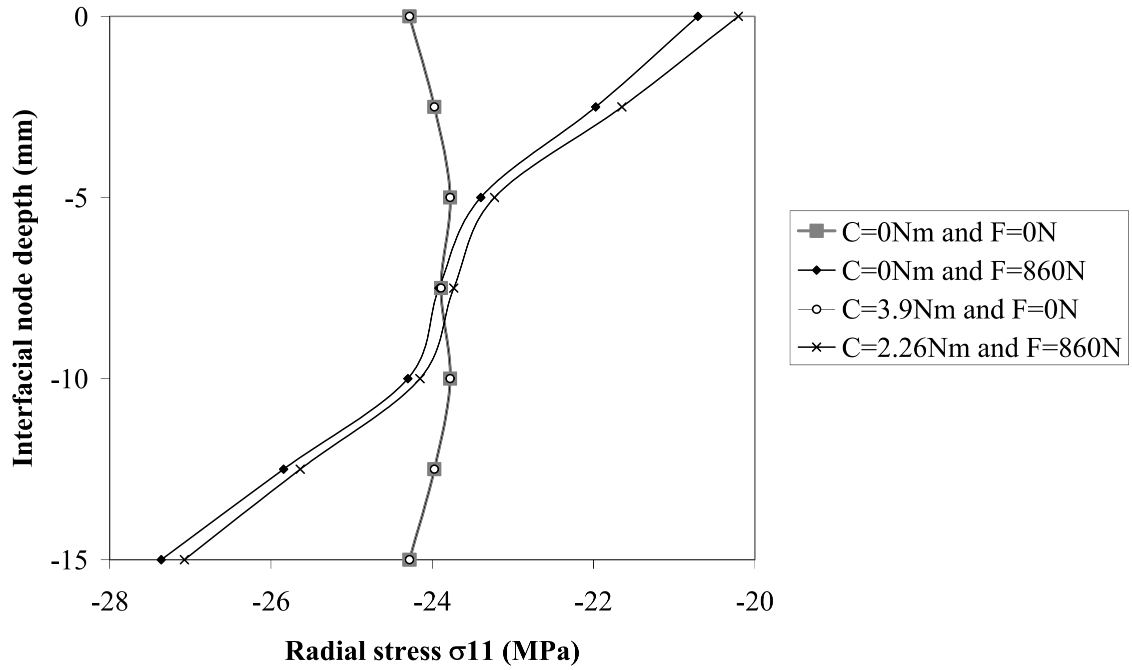

Fig. 10: Finite element radial stress σ_{11} at the post/HDPE interface for different loading conditions.

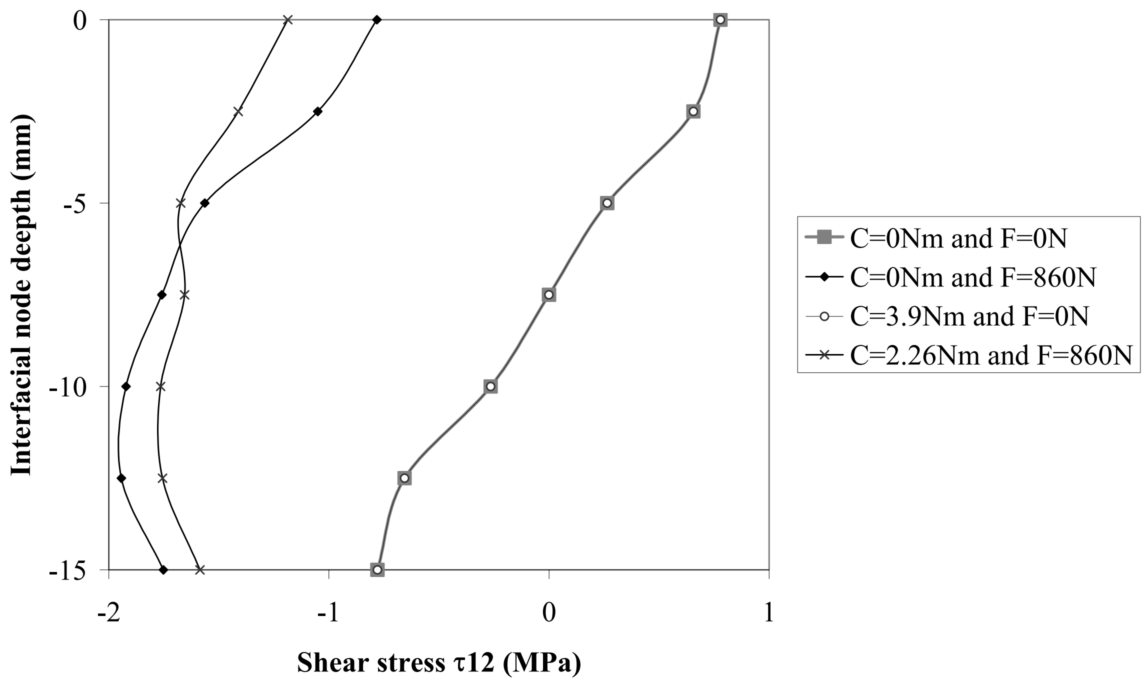

Fig. 11: Finite element shear stress τ_{12} at the post/HDPE interface for different loading conditions.

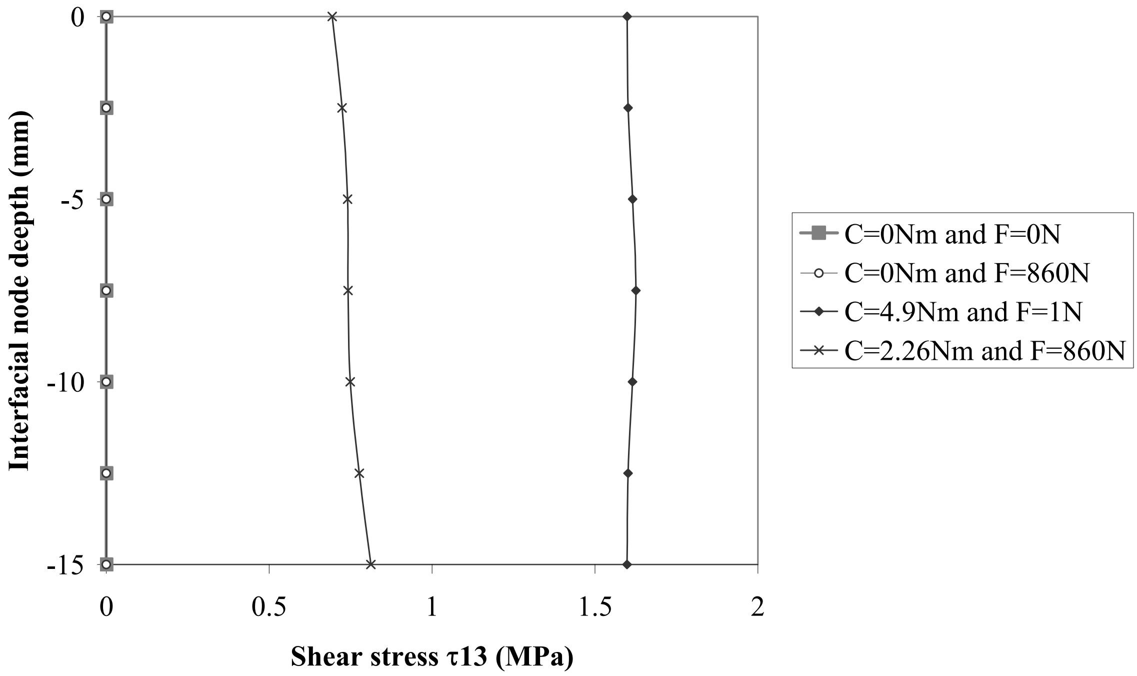

Fig. 12: Finite element shear stress τ_{13} at the post/HDPE interface for different loading conditions.