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3D numerical investigation into the seismic behaviour of tunnels in natural soils

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ABSTRACT: Extensive research has been directed to two-dimensional (2D) modelling of tunnel behaviour subjected to seismic loading. However, the propagation of seismic waves has an arbitrary direction with respect to the axis of the tunnel structure, which causes multi-directional loading of the soil deposit and the tunnel lining. 2D simplifications of these three-dimensional (3D) effects can have a significant impact on the prediction of the tunnel seismic response. Furthermore, most natural soils are characterised by high stiffness and peak strength due to their initial structure. Extreme events, such as earthquakes, can induce sufficient material stiffness degradation, which may significantly alter the soil-tunnel response. Such complex mechanical behaviour cannot be captured by simple elasto-plastic models, thus the need for a more advanced constitutive modelling able to include the initial soil structure and its subsequent degradation during non-monotonic loading. This paper presents novel results obtained from fully coupled non-linear 3D numerical simulations of a shallow circular tunnel in natural clays accounting for damage to structure induced by earthquakes.

Keywords: 3D FEM; seismic tunnel behaviour; soil destructuration; kinematic hardening model; natural clays

1 INTRODUCTION

Advances in computer and software technology have enabled numerical solutions of the seismic performance of tunnels overcoming the limitations imposed by the earlier methods (i.e., closed-form and analytical solutions), with most researchers focusing on 2D approaches. However, when the direction of wave propagation is arbitrary with respect to the axis of the tunnel, longitudinal effects (e.g., spatial incoherence, axial compression and extension, longitudinal bending, construction sequence) can considerably impact the response of the tunnel structure and these effects should not be ignored. Similarly, the multi-directional cyclic shearing of a soil deposit induced by seismic actions can also significantly affect the soil-tunnel interaction. In order to account for these 3D effects, 2D approaches may require simplifications which can lead to a significant underestimation of the tunnel lining forces. With the availability of high-performance computing resources, 3D numerical approaches are now increasingly employed to address complex problems.

The simple visco-elastic or elasto-plastic assumptions (e.g., Mohr-Coulomb, Modified Cam Clay, etc.) usually adopted in the simulation of soil-tunnel interaction problems do not accurately predict the complex mechanical behaviour of natural soils under cyclic loading, such as non-linearity, early irreversibility, anisotropy, pore pressure build-up, decrease of nominal stiffness, related hysteretic energy dissipation, and, in particular, soil structure degradation. Intact natural soils, and specifically structured clays, have an initial structure which enables them to exist at states outside the state boundary surface, resulting in higher strength and initial small-strain stiffness than reconstituted materials (Leroueil and Vaughan, 1990; Nash et al., 2007; Brosse et al., 2017). External loading and disturbance can cause the degradation of initial structure, inducing irrecoverable plastic strains in the soil deposit. As the destructuration progresses, the inter-particle bonding of the soil further deteriorates with an associated sharp reduction in material strength and stiffness (Leroueil et al., 1979). Intense seismic loading can cause the destructuration to accelerate which, in turn, can alter the performance of tunnels built in structured soil deposits. Ignoring this effect, in conjunction with a simplified 2D spatial discretisation, can lead to incorrect predictions of the ground deformations, thus resulting in unconservative estimates of the lining loads.

In this paper, the dynamic performance of a shallow circular tunnel in a natural clay deposit subjected to multi-directional seismic loading is analysed by means of a 3D non-linear finite element (FE) approach. To account for the effect of soil structure degradation, the advanced constitutive model formulated within the framework of kinematic hardening multi-surface plasticity for natural clays (RMW) by Rouainia and Muir-Wood (2000) has been employed in the numerical simulations. The RMW model can effectively reproduce the key features of cyclic behaviour of natural clays such as the decay of shear stiffness with strain amplitude, the corresponding increase of hysteretic damping and the related accumulation of excess pore water pressure and structure degradation under undrained conditions (Elia and Rouainia, 2016). Its performance in cyclic/dynamic conditions has previously been explored in 2D analyses by Elia and Rouainia (2012), Elia and Rouainia (2014) and Cabangon et al. (2019). This is the first time that the constitutive model has been adopted in 3D dynamic simulations.

The 3D tunnel model is firstly validated against the 2D counterpart to check the effectiveness of the adopted boundary conditions. The results of the 3D numerical simulations predicted during the simultaneous application of two horizontal input motion components are then compared with those obtained when only one component of the same input is applied in the transverse direction. More importantly, the influence of damage to structure on the tunnel lining forces due to multi-directional earthquake loading is investigated.

2 NUMERICAL MODEL

The case of a shallow circular tunnel, 10m in diameter with 15m soil cover, within an ideal 70m thick deposit of Avezzano clay overlying a rigid bedrock, has been considered in all simulations. The lining has been assumed to be made of precast concrete segments 0.5 m thick, modelled as a linear visco-elastic material with Young's modulus = 38 GPa, Poisson's ratio = 0.25 and damping ratio = 5%. The Avezzano clay, a structured natural soil in the highly seismic area of central Italy, is geologically normally consolidated with its silty clay layers characterised by very low plasticity (i.e., PI ~ 10%) and high values of calcium carbonate content (i.e., $CaCO_3$ content between 60 and 80%). The RMW model has been previously calibrated for the Avezzano clay by Cabangon et al. (2019) based on the works by Burghignoli et al. (2003) and Elia and Rouainia (2014), considering a series of laboratory results reported by Burghignoli et al. (1999), D'Elia (2001) and Burghignoli et al. (2010). The calibrated RMW model parameters adopted in the FE non-linear dynamic simulations are given in Table 1. The anisotropy of the initial structure has been neglected for simplicity, assuming an inherently isotropic behaviour of the soil.

The 3D model has been discretised with a total number of 189,746 linear strain 10-node tetrahedral elements. To ensure that the seismic wave is transmitted accurately through the FE mesh, the vertical distance between adjacent nodes has been limited to satisfy the condition recommended by Kuhlemeyer and Lysmer (1973). Standard boundary conditions have been adopted for the static analyses. In the dynamic simulations, the bottom of the model has been assumed rigid (i.e., simulating, in this ideal case, a high impedance contrast between the soil deposit and the seismic bedrock), while the viscous boundaries proposed by Lysmer and Kuhlemeyer (1969) have been used along the lateral sides of the mesh to absorb the outgoing wave energy and, thus, avoiding spurious wave reflections (as tied-nodes are not available in PLAXIS 3D and the free-field boundaries were showing problems at the corners of the 3D model at the time of the simulations). In addition, parametric studies have been conducted to optimise the lateral extent of the 3D model in both the transverse and longitudinal directions and to ensure that the boundaries are significantly far enough from the tunnel to properly simulate free-field conditions at the edges of the model. The well-known equation proposed by Viggiani and Atkinson (1995) is used to describe the small-strain shear stiffness of the soil deposit with depth. The dimensionless parameters A, n and m in the Viggiani and Atkinson equation have been set equal to 2150, 0.78 and 0.22, respectively, based on a plasticity index PI = 10% for the Avezzano clay. The water level has been assumed to coincide with the ground surface. Figure 1 shows the FE model implemented in PLAXIS 3D (Brinkgreve et al., 2015).

Table 1. RMW parameters for Avezzano clay

Parameter/ symbol	Physical contribution/ meaning	Value
M	Critical state stress ratio for triaxial compression	1.42
λ^*	Slope of normal compression line in ln$v$-ln$p$ compression plane	0.11
κ^*	Slope of swelling line in ln$v$-ln$p$ compression plane	0.016
R	Ratio of size of bubble and reference surface	0.4
B	Stiffness interpolation parameter	15.0
ψ	Stiffness interpolation exponent	1.45
η_0	Anisotropy of initial structure	**0.0**
r_0	Initial degree of structure	5.2
A^*	Parameter controlling relative proportion of distortional and volumetric destructuration	0.2
k	Parameter controlling rate of destructuration with damage strain	1.5

The signals recorded at the Ulcinj-Hotel Albatros station during the 1979 Montenegro earthquake have been selected to explicitly match the response spectrum provided by Eurocode 8 at the first natural period of the soil deposit T_1 (equal to 1.03 s), which has been calculated according to the visco-elasticity theory (Roesset, 1977).

The time histories of the E-W and N-S components of the earthquake and their response spectra are illustrated in Figure 2. The two motion components have been filtered to prevent frequencies higher than 10 Hz and scaled up to 0.30g to simulate a strong seismic motion occurring at the site. Table 2 gives general information about the two input motions.

To consider the effects of pre-seismic stress states, a static analysis in undrained conditions has been initially conducted to simulate the tunnel excavation and the installation of the tunnel lining (wished-in-place). Subsequently, the dynamic analyses have been carried out under undrained conditions with a time step corresponding to that of the input signals. The scaled acceleration time histories have been imposed at the rigid bedrock level. In particular, the N-S component of the earthquake has been applied in the transverse x-direction of the model, while the E-W component has been imposed in the longitudinal y-direction. A Rayleigh damping of 2% has been added to avoid the propagation of spurious high frequencies and to compensate for the RMW underestimation of the hysteretic dissipation in the small-strain range (Amorosi et al., 2010).

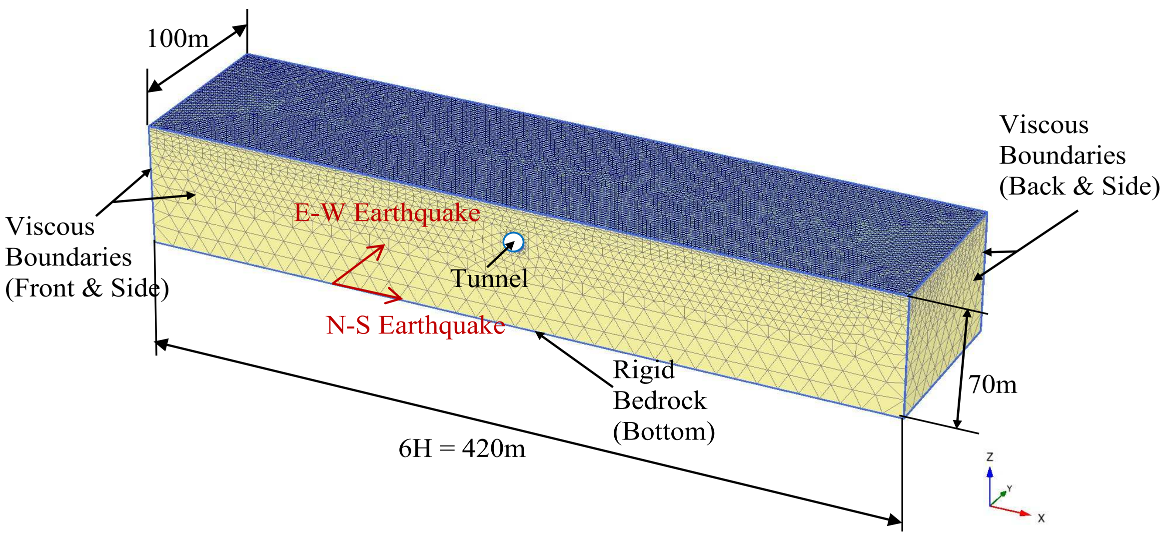

Figure 1. FE model and lateral boundary conditions for the dynamic simulations (after Cabangon et al., 2018)

Table 2. Main characteristics of the selected earthquake signals

Station	Earthquake	Magnitude (M_w)	Epicentral distance (km)	Component	Arias intensity I_a (m/s)	Duration T_{90} (s)	a_{max} (g)	v_{max} (m/s)
Ulcinj-Hotel Albatros	Montenegro (1979)	6.9	19.7	N-S	0.729	12.3	0.181	0.176
				E-W	0.784	12.2	0.224	0.263

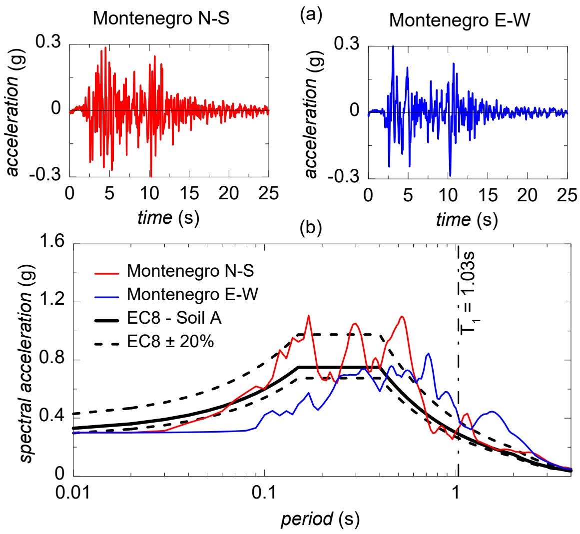

Figure 2. (a) N-S and E-W input motion acceleration time histories and (b) response spectra (after Cabangon et al., 2018)

3 RESULTS AND DISCUSSIONS

3.1 *Comparison between 2D and 3D results*

The profiles of the minimum and maximum horizontal accelerations (a_x and a_y) and vertical acceleration (a_z), obtained in free-field conditions with a 2D using tied nodes and a 3D model (denoted as 3D – x in the graphs), are presented in Figure 3. These profiles are recorded along the soil depth when the N-S component of the earthquake event is applied in the transverse x-direction. The 2D and 3D results are in good agreement, although the 3D accelerations are generally smaller than those obtained from the 2D model as depicted in Figure 3(a). This can be attributed to the generation of seismic waves in the longitudinal direction due to Poisson effects when the input motion is applied in the transverse direction of the 3D model, which cannot be modelled in a 2D approach. As such, a horizontal acceleration, a_y, propagating in the y-direction is generated in the 3D model as shown in Figure 3(b), where a maximum value of about 0.05g is predicted at the surface. In addition, parasitic vertical accelerations due to wave reflection, a_z, reaching a max value of 0.07g at surface, are recorded during both the 2D and 3D simulations (Figure 3(c)).

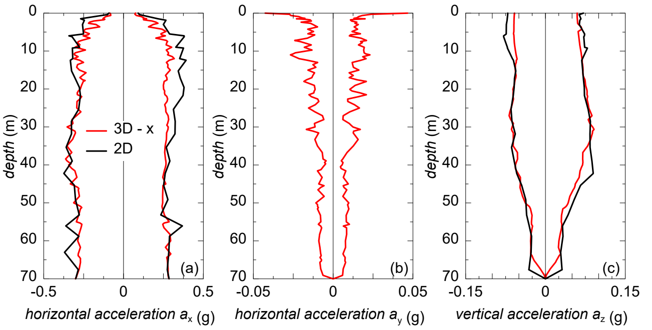

Figure 3. Profiles of max and min accelerations recorded in free-field conditions when the N-S component is applied transversely: (a) a_x; (b) a_y and (c) a_z

Figure 4 shows the distribution of the predicted hoop force, transverse bending moment and transverse shear force at the end of the seismic event as a function of the angle θ (defined positive in anti-clockwise direction) as well as the maximum and minimum force envelopes (shown with dashed lines).

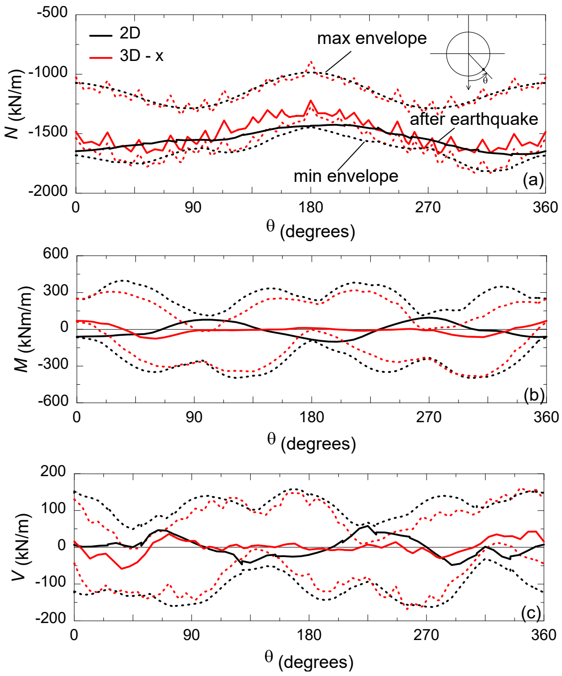

Figure 4. Distribution of max and min (a) hoop forces; (b) transverse bending moments and (c) transverse shear forces when the N-S component is applied transversely

The hoop forces at the central tunnel section predicted by the 3D model are relatively smaller compared to those from 2D. Also, the 3D transverse bending moments and shear forces are comparable but are generally lower than the corresponding values from 2D model due to the generation of the earthquake accelerations in the longitudinal direction. However, the 2D and 3D residual bending moments and shear forces after the earthquake do not match well and the locations of the peak residual values around the lining do not align (Figure 4(b-c)). Nevertheless, these differences between 2D and 3D results do not affect the predicted force envelopes, which are more important for the tunnel design.

The 3D propagation of the horizontal acceleration in the y-direction generates longitudinal forces in the lining (i.e., longitudinal axial force, longitudinal bending moment, longitudinal shear force, torsional moment, and in-plane shear force), which cannot be captured in a 2D model. The longitudinal axial forces are significant and can reach maximum values of 1433 kN/m in compression and 674 kN/m in tension (Figure 5(a)). The longitudinal bending moments can also be as large as 142 kN-m/m (Figure 5(b)). Ignoring these forces may lead to under-designing the tunnel lining, thus potentially compromising the integrity of the structure.

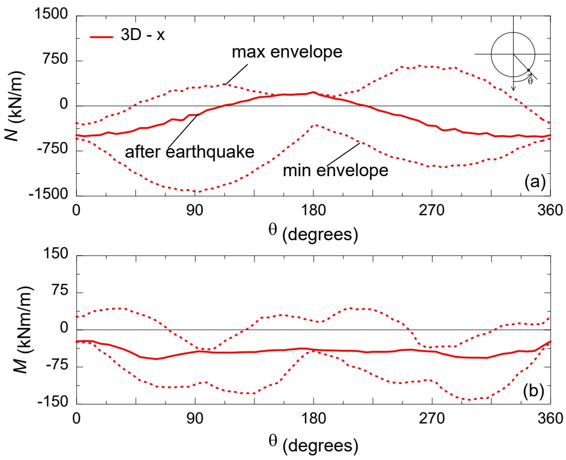

Figure 5. Distribution of max and min forces when the N-S component is applied transversely: (a) longitudinal axial forces and (b) longitudinal bending moments

3.2 Multi-directional loading effects

Figure 6 illustrates the minimum and maximum accelerations recorded along the depth in free-field conditions obtained by the 3D model and applying the input motions separately or simultaneously. The effect of the N-S and E-W components applied simultaneously at the bedrock (3D – xy) are apparent for the transverse accelerations, a_x, which are generally smaller than those obtained when a single component is applied only in the transverse direction (3D – x), as shown in Figure 6(a). However, the 3D – xy analysis revealed a much higher degree of destructuration around the tunnel at the end of the earthquake (Figure 7, where the RMW parameter r at the beginning of the dynamic analyses starts from almost its initial value of 5.2). This further reduces the soil shear stiffness as the shear strains increase, which in turn causes a higher dissipation of the accelerations in the longitudinal direction (Figure 6(b)). In contrast, similar vertical accelerations, a_z, are predicted by both 3D models, as illustrated in Figure 6(c).

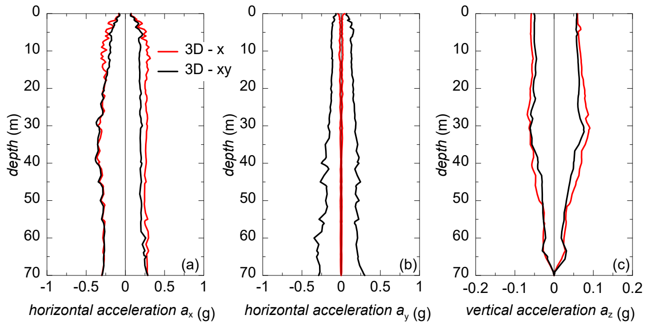

Figure 6. Profiles of max and min accelerations recorded in free-field conditions when the N-S component is applied transversely and both N-S and E-W components are applied simultaneously: (a) a_x; (b) a_y and (c) a_z

The response in terms of accelerations correlates well with the resulting lining forces in the tunnel. The maximum and minimum values of the hoop forces, transverse bending moments and transverse shear forces due to the simultaneous application of the two horizontal components are generally smaller than those obtained in the 3D – x analysis, as shown in Figure 8. This is related to the increase in the amount of destructuration predicted and, consequently, the higher seismic wave dissipation in the y-direction during the 3D – xy simulation. This could not be captured by the Modified Cam-Clay model, which was adopted in Cabangon et al. (2018) to simulate the mechanical behaviour of the same soil deposit, as the limited accumulation of plastic strains predicted by a simple single surface model prevents the dissipation of the transverse accelerations in the longitudinal direction.

Therefore, the maximum longitudinal compressive forces in the lining increase by as much as 805 kN/m between θ = 0° and 90° and between 270° and 360°, while the maximum longitudinal tensile forces increase by approximately 743 kN/m between θ = 90° and 270° (Figure 9(a)). In addition, the in-plane shears (Figure 9(b)) rise by as much as 608 kN/m. The longitudinal axial forces and the in-plane shears are both crucial for the design of the circumferential bolted joint connections in segmental linings.

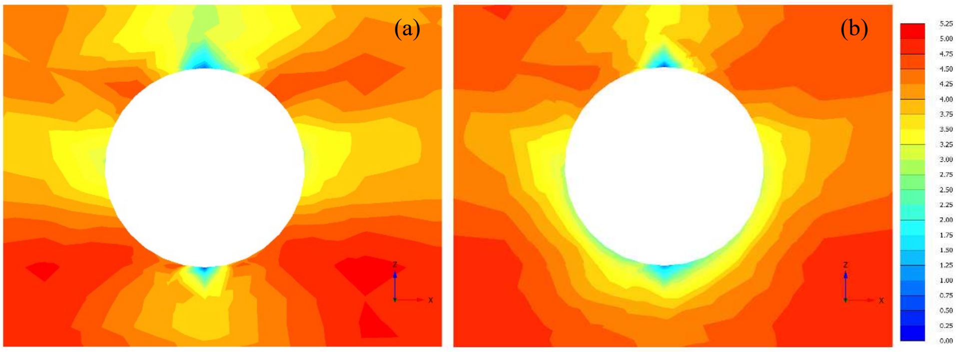

Figure 7. Contours of the destructuration parameter, r, at the end of the seismic event around the tunnel when (a) the N-S component is applied transversely and (b) both N-S and E-W components are applied simultaneously

4 CONCLUSIONS

This paper has presented a numerical analysis of a shallow circular tunnel in a natural clay accounting for damage to soil structure under seismic conditions. The main conclusions are as follows:

- The 2D lining forces are found to be more conservative than those predicted with 3D models, i.e., generally higher in magnitude, due to the inability to disperse the seismic wave and dissipate the energy longitudinally. This observation justifies the common practice to rely on a 2D approach in designing the tunnel section under seismic conditions. On the other hand, the smaller transverse forces obtained from the 3D models translate into a more cost-effective lining design.
- The generation of the seismic wave in the longitudinal direction when the input motion is applied in the transverse direction produces longitudinal forces in the lining. These cannot be predicted using a 2D approach. In addition, the presence of an initial structure in natural clays and its subsequent degradation during loading causes the dissipation of the transverse earthquake acceleration in the longitudinal direction. When both the transverse and longitudinal component of the earthquake are applied simultaneously, a much higher degree of destructuration is observed. This, in turn, reduces further the soil shear stiffness resulting in a relatively higher longitudinal horizontal acceleration. As a consequence, some of the longitudinal forces, particularly the longitudinal axial force and in-plane shear, substantially increase in magnitude and become crucial in influencing the decision on the size of the tunnel lining and the design of the joints.

In general, the proposed 3D multi-directional FE dynamic scheme accounting for the degradation of the initial soil structure can realistically capture the arbitrary direction of the seismic wave and the complex spatial behaviour of tunnels in structured soils during earthquake loading, which a 2D numerical model can underestimate or even ignore. The study not only highlights the importance of considering the multi-directional effects of the seismic action in tunnel design but also the massive influence of soil destructuration on the soil-tunnel interaction during earthquake loading. Hence, it enables to improve the accuracy and reliability in predicting the tunnel behaviour during dynamic actions, thereby ensuring the safety of the tunnel during an earthquake event.

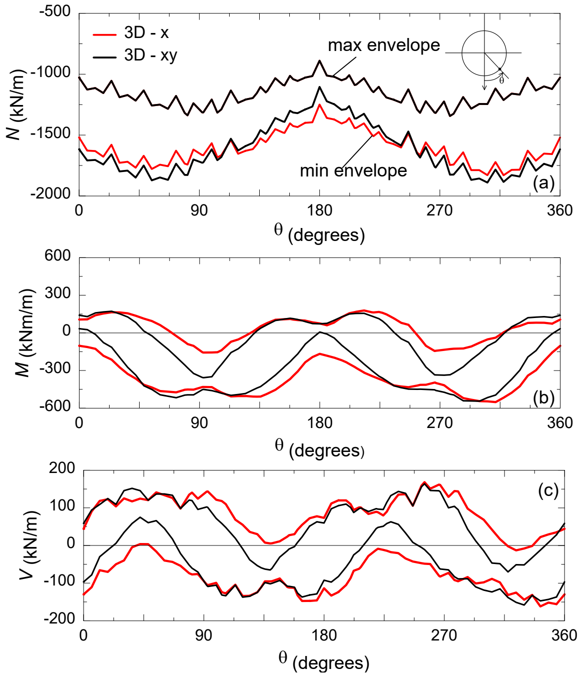

Figure 8. Distribution of max and min (a) hoop force; (b) transverse bending moment and (c) transverse shear force when the N-S component is applied transversely and both N-S and E-W components are applied simultaneously

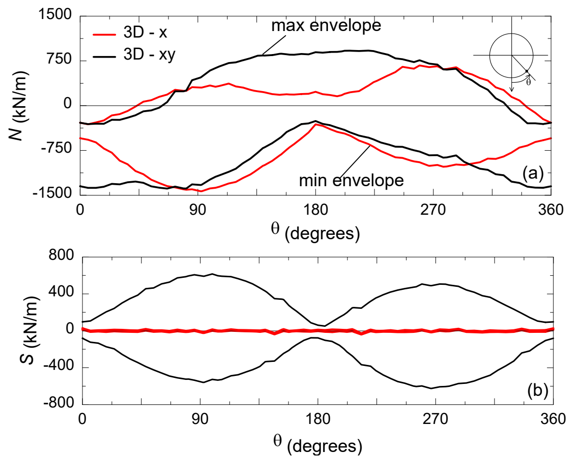

Figure 9. Distribution of max and min (a) longitudinal axial force and (b) in-plane shear when the N-S component is applied transversely and both N-S and E-W components are applied simultaneously

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