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Mechanics of the Interaction between a Nuclear-Waste Disposal Container and a Buffer During Discontinuous Rock Movement

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ABSTRACT

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The study of the complex geomechanical interactions that take place within a borehole environment of a nuclear-waste disposal vault is crucial to the long-term safety and efficiency of a waste emplacement scheme. This paper presents a theoretical investigation of the interaction between a container shell and the surrounding buffer region which can be induced by discontinuous movement at a fracture plane which intersects a disposal vault borehole. The theoretical studies presented in the paper illustrate the influence of factors such as the mechanical properties of the buffer, surcharge loads on the surface of the buffer, and characteristics of the buffer–container and buffer–rock interfaces, on the stresses that are generated in the container.

INTRODUCTION

The development of containment technologies for the long-term storage and disposal of irradiated fuel is an area of research which is of crucial importance to the nuclear energy industry. The Fuel Waste Technology branch of Atomic Energy of Canada Ltd. (AECL) is the leading agency for the development of the necessary containment technologies (Hancox, 1986). The Canadian proposals for the disposal scheme specifically concentrate on the deep burial (approximately at 1000 m at depth) of the waste in specially constructed vaults in plutonic rocks of the Canadian Shield. The engineered multi-barrier concept constitutes a key feature in the waste disposal effort. Current proposals for the disposal facility involves four principal components, which include the vault system, the waste container, the backfill material and the buffer material. The functional requirements of the various components of the system are fully documented in the literature (see e.g. Selvadurai, 1988a,b). The buffer material which fills the space between the waste container and the borehole walls is a mixture of bentonitic clay and sand which should fulfill certain functional criteria. It should act as a barrier to suppress the detrimental effects of the corrosive water in the host rock and enhance the life of the

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waste container; serve as a geochemical filter for the sorption of radionuclides released either by accidental damage or natural breakdown of the waste containers; provide the mechanical strength to support the waste containers; isolate the containers from detrimental rockmass movements; act as a medium for conducting the radiogenic heat; and it should be capable of swelling under fluid influx to seal gaps, cavities etc., that may develop by moisture depletion during the heat and moisture transfer processes.

This particular research focusses on the investigation of the manner in which the buffer is capable of isolating the waste container from detrimental effects of rockmass movements. The plasticity of the buffer region is an important aspect particularly in relation to the isolation of the waste container from detrimental rockmass movements. Such rock movements can take place either due to the thermal loading of the repository area induced by the stored waste, removal of ground water from the repository area, earthquake effects or by stress relief due to the creation of the repository. Estimates indicate that rockmass movements due to thermal loadings can be of the order of 2 to 5 cm. Such displacements can occur in a discontinuous fashion when fractures are generated and/or reactivated by the thermal loadings. In the particular instance when a fracture intersects the borehole, a dislocation type rock movement can prematurely threaten the integrity of the waste container. Furthermore, the experimental investigations conducted in connection with heat and moisture migration in the buffer in the absence of moisture influx (Selvadurai, 1988a,b) indicate that loss of moisture in the buffer region leads to a severe loss of its "plasticity" properties. Therefore, a discontinuous movement that can take place under conditions with no moisture influx into the buffer region but moisture loss due to heating, can present an adverse environment for the waste container. The theoretical modelling of the effects of such discontinuous rock movements on the behaviour of the buffer-container system should take into consideration a number of complex material and interface phenomena. These include: (1) the mathematical representation of the changes in the deformability and failure (fracture/yield) characteristics of the buffer associated with the moisture depletion; (2) investigation of the extent of separation and fracture that is associated with the moisture depletion process; (3) non-linear processes that exist at the buffer-container and buffer-rockmass interfaces; (4) changes in the geometry of the buffer due to heat induced shrinkage processes; (5) elastic and plastic deformations of the container which account for large deflections and large strains; and (6) development of fracture and separation zones at the various interfaces due to the discontinuous rock deformation.

A theoretical modelling (analytical/numerical) of the buffer-container interaction which takes into account all the non-linear thermomechanical processes outlined above presents a problem of formidable complexity. The objective of this paper is to provide an elementary treatment of this rather complex buffer–container interaction problem with a view to providing an assessment of the possible influence of the discontinuous rock movement on the stresses generated in the container shell. The paper specifically examines the interaction of a container shell and the buffer which possesses elastic-plastic material properties. A non-linear finite element technique is used to assess the manner in which the location of the fracture planes, surcharge loads at the borehole surface, variable interfaces at the buffer–container and buffer–rock surfaces and non-linear material characteristics of the buffer material influence the stress induced in the container shell by discontinuous rock movement.

NUMERICAL MODELLING

Attention is focussed on the problem of an axisymmetric single borehole configuration as shown in Fig.1. The geometries of the borehole and the container are selected to conform approximately to those proposed for the Canadian concepts (Wardrop et al., 1985). The action of the backfill is represented purely as a surcharge which acts at the surface of the buffer region. The fracture plane in the rockmass, along which the discontinous rock movement takes place, is oriented horizontally (Fig.2). For purposes of illustration, the location of the discontinuity is assumed to be at the midway point of the borehole. The discontinuous deformation corresponds to a differential displacement Δ which induces a state of symmetry about the X–Z plane. In the modelling, the region below the discontinuity is held stationary and the upper half is allowed to displace in the horizontal direction. It is assumed that the fracture plane offers no resistance to the movement. In the ensuing, the modelling of the various components of the idealization of the buffer–container–rockmass configuration will be briefly discussed.

THE ROCKMASS

The stiffness and strength characteristics of the rock are expected to be significantly higher than those of the buffer region. In the numerical computations, the Young modulus of the rock is set equal to 10^9 MPa and the Poisson ratio is set equal to 0.48. The rockmass is assumed to behave elastically

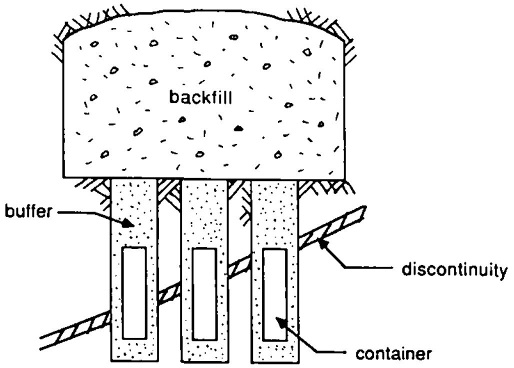

Fig.1. Possible orientation of plane of discontinuity to disposal vault borehole.

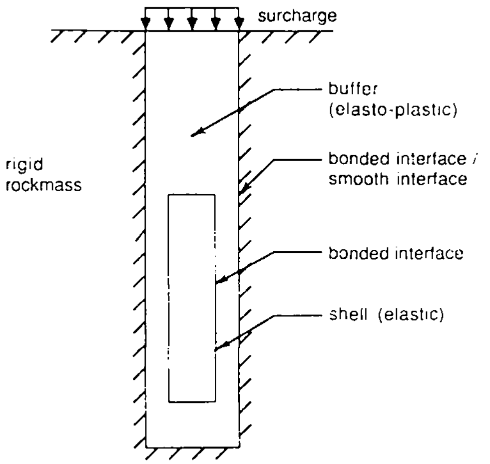

Fig.2. Schematic representation of an idealized disposal vault borehole.

throughout the analysis. Since the rockmass is modelled as essentially a rigid region, a horizontally directed distributed load is applied to induce the relative displacement.

BUFFER REGION

The buffer material is a mixture of bentonitic clay and quartz sand. The mix composition of the buffer is organized in such a way that the functional requirements of mechanical strength, permeability, swelling capabilities and heat conduction are simultaneously satisfied. The mechanical behaviour of the buffer can be influenced by a variety of factors including grain-size distribution, soil micro-structure, stress history, moisture content and degree of saturation. These factors contribute to soils which display marked non-linear and irreversible time-dependent phenomena. It is evident that any attempt to solve the container–buffer–rockmass interaction problem by taking into account all such characteristics is a complex task. It is therefore prudent to idealize the mechanical behaviour of the buffer mass in order that progress in the analytical treatment of these soil structure interaction problems can be made within reasonable computational efforts. In these studies the critical state model (or the modified Cam-clay model) is chosen to model the time independent mechanical behaviour of the buffer material. Details of the formulation and numerical implementation of this model are given by Roscoe and Burland (1968) and Desai and Siriwardane (1984).

In the numerical implementation of such models, the accuracy largely depends on the exactness of the input parameters. With regard to the constants used in the constitutive model based on the Critical State model, it is required to determine the shear strength parameters and the stress-strain properties of the soils. Both conventional triaxial compression tests and direct shear tests can be employed to determine the relevant mechanical parameters.

Pang and Selvadurai (1990) have reported the results of a series of geotechnical laboratory tests on the compacted buffer material. Graham et al. (1986), Sun (1986) and Wan (1987) have also reported some geotechnical laboratory test results for the buffer mixture. The results of these investigations form the basis for estimating the mechanical parameters that will be used in the numerical studies. It may be noted that changes in initial dry density, void ratio and residual compaction stresses can lead to variations in the estimated parameters.

For the modified Cam-clay model, seven basic parameters need to be specified; these include M, λ, κ, p_0, e_0 and the basic elastic parameters E and ν. The data is obtained from two separate sources: (1) laboratory tests on the buffer mixture compacted to a maximum dry density of 1.76 Mg/m^3 at an optimum moisture content of 18%; (2) similar tests on buffer mixture compacted to a dry density of 1.51 Mg/m^3 at a moisture content of 28%. As reported by Pang and Selvadurai (1990), for the denser buffer material, the Young modulus of the buffer is found to be approximately 140 MPa with a Poisson ratio of 0.45. From the plot of $\sqrt{3J_{2D}}$ vs $J_1/3$, M is estimated to be 0.4. From the results of certain parametric studies, the initial void ratio is found to exert a relatively little influence; as such it is assigned a value of 1.0. The initial stress in the buffer, p_0, is assigned a value of 100 kPa as a first approximation of the stresses due to compaction. The quantity κ can be estimated from the following relationship.

$$K = \frac{p_0(1 + e_o)}{\kappa} \qquad (1)$$

where K is the bulk modulus obtained from the hydrostatic test results reported by Pang and Selvadurai (1988). The values of 0.0025 and 0.0005 are used for λ and κ, respectively. From the results reported in the references cited earlier, the Young modulus is determined to be 50 MPa (average value) and the Poisson ratio is set equal to 0.48. Since there is a scarcity of data of principal stress, at the 'critical state', M is taken as 1.0. Similarly p_0 is assigned a value of 100 kPa. From the tentative Critical State line proposed in Graham et al. (1986), an e_0 value of 3.0 and a λ value of 0.50 are used. Since the swelling procedure is not performed during the isotropic consolidation tests, the κ value of 0.15 is also estimated from eq. 1. A summary of the material parameters employed to model the two densities of the buffer region is given in Table I.

INTERFACE CONDITIONS

Two extreme conditions of the buffer–rockmass interface are considered, namely perfectly "rough" and perfectly "smooth". The rough case is simulated by restricting the relative movement between the buffer and the rockmass in the vertical, or z-direction. The smooth case is simulated by allowing vertical displacement through the use of rollers at the boundaries. The latter configuration allows the surcharge to take effect over the entire buffer region. It should also be noted that the analysis focusses on a single cell of the vault

TABLE I

Summary of material parameters

Problem category	Elasticity		Critical state					Surcharge (MPa)
	E (MPa)	ν	M	λ	κ	e_0	p_0 (MPa)	
A	140	0.45	0.4	0.0025*	0.0005*	1.0	0.1*	
B	140	0.45	0.4	0.0025*	0.0005*	1.0	0.1*	0.1
C	50	0.48	1.0*	0.50	0.15	3.0	0.1*	
D	50	0.48	1.0*	0.50	0.15	3.0	0.1*	0.1

*Estimated.

configuration and that the influence of neighbouring cells is neglected. During the container–buffer rockmass interaction, the cylinder would experience a rigid body translation. The boundary between the container and the buffer could exhibit a variety of interface characteristics ranging from completely smooth to completely bonded conditions. In the present investigation, the interface is assumed to be in a fully bonded condition.

WASTE CONTAINER

One container option under study is the supported-shell metal matrix concept. This concept involves the packing of the used fuel bundles into a thin, corrosion-resistant shell and casting the remaining space with a low melting point metal or alloy. Structural support for the shell is provided by the resulting metal matrix. Several materials have been identified for fabrication of the corrosion-resistant shell, including commercially available pure and low alloy titanium, high nickel-based alloy such as Inconel 625 and pure copper. A conceptual design has also been produced for a copper shell structurally supported container (Ko and Hosaluk, 1987). The ensuing finite element analysis focusses on the performance of the copper cylindrical shell. According to the conceptual design, the prototype metal-matrix container has a relatively thick shell of more than 25 mm in order to provide adequate mechanical strength and corrosion allowance. In the present analyses, the waste container is modelled as a cylindrical shell with an average thickness of 25 mm. Material properties for copper are used for all the analyses; a Young modulus of 99,000 MPa and Poisson ratio of 0.35. The shell is assumed to behave as a linear elastic material throughout the dislocation type movement of the system.

FINITE ELEMENT MODELLING

The main objective of this paper is to investigate the buffer–container–rockmass interaction problems due to distress caused by dislocation type movements along fracture planes intersecting nuclear waste disposal vault boreholes (Fig.1). Due to symmetry, only one half of the borehole needs to be discretized. The effect of the backfill is modelled as a surcharge at the upper surface of the buffer. A schematic diagram of the idealized disposal vault borehole is shown in Fig.2. Fig.3 shows the finite element mesh used in the analyses. These are 48 solid "brick" elements and 26 shell elements resulting in 380 nodes. The boundary conditions are such that the half of the borehole below the plane of discontinuity is restrained from lateral movement. The upper half only is allowed to move horizontally in the x-direction by the application of horizontal loadings applied to the solid elements that are used to simulate the rockmass surrounding the borehole. The plane of discontinuity is assumed to be located at the mid-section level of the borehole. The container and the buffer region are modelled by superparametric Ahmad-type general shell elements and 20-node isoparametric brick elements, respectively. One of the major advantages of this element is its capability to model curved and irregular boundaries owing to the presence of a midside variable node at each edge of the elements. Details of the numerical techniques are given by Pang (1989), and Selvadurai and Pang (1990).

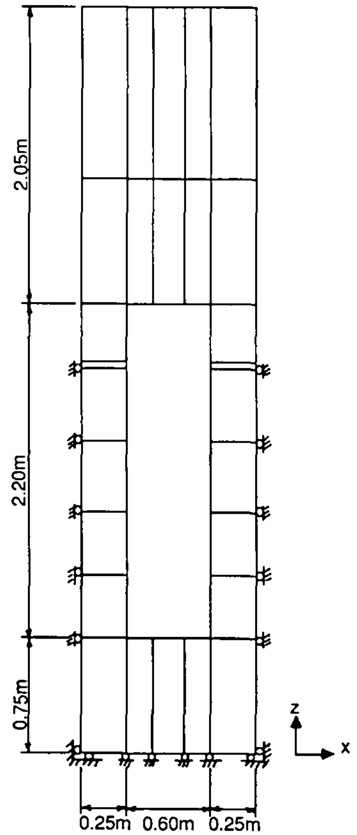

Fig.3. Finite element discretization of disposal vault borehole.

NUMERICAL RESULTS

In the three-dimensional finite element analyses, the results of linear elastic analyses of the corresponding buffer–container interaction problems are used as a basis for comparison. As discussed previously, the modified Cam-clay constitutive model is used to simulate the buffer behaviour. The analyses focus on the evaluation of critical stresses in the container and the soil pressure at the container–buffer interface. These stresses are the longitudinal stresses (σ_{zz}) and the hoop stresses ($\sigma_{\theta\theta}$) in the container as well as the radial soil stresses (σ_{rr}) around the cylinder.

Figs.4 and 5 illustrate the manner in which the maximum stress in the axial direction of the container varies with the magnitude of the displacements of the surrounding rockmass. The stresses are normalized with respect to E_c, the Young modulus of the container (copper), and the displacement is normalized with t, the thickness of the container. The value of D/t is held fixed at 24, this corresponds to a relatively thick shell. The modular ratio E_c/E_b, where E_b is the Young modulus of the buffer region, is set equal to 2000 and 700. The non-linear constitutive model is implemented by using 6 equal load increments with 2 iterations each increment. A surcharge of 100 kPa is applied on the upper surface of the buffer to simulate the effects of a 5 m height of backfill material.

In general, distinct non-linearities are observed in the curves from the analyses which incorporate non-linear effects in the buffer behaviour. The

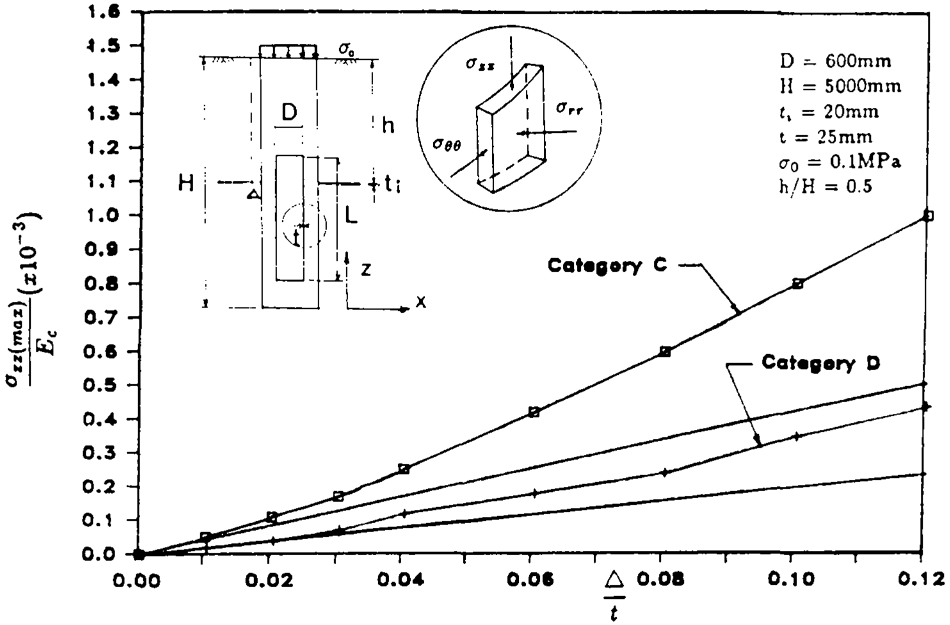

Fig.4. Maximum longitudinal stress vs. displacement ($E_c/E_b = 2000$).

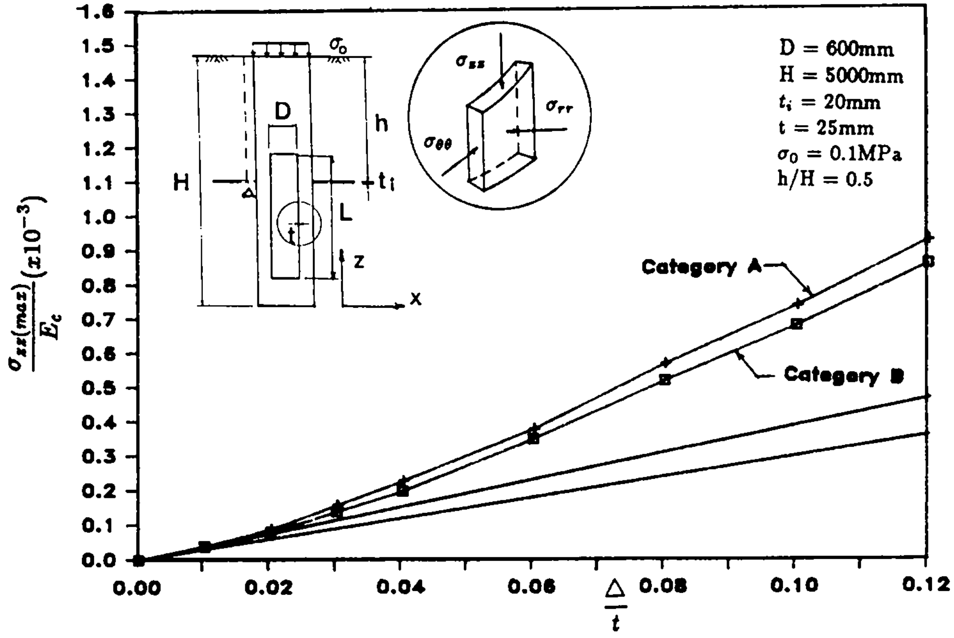

Fig.5. Maximum longitudinal stress vs. displacement ($E_c/E_b = 700$).

results show that a stiffer container (lower E_c/E_b) would experience higher longitudinal stresses. Moreover, the surcharge load tends to reduce the maximum stresses induced in the container. It is clear that the backfill contributes to the structural integrity of the container during the dislocation type rock movement. In general, the increase in stresses predicted by the non-linear analyses becomes significant as the induced displacements are increased. Thus for this particular type of container loading, the linear elastic solution does not give rise to conservative estimates for the container stresses. Figs.6 and 7 indicate that for the situations modelled and for the range of displacements considered, the maximum hoop stress in the container is relatively uninfluenced by the modular ratio E_c/E_b. Also for a given displacement, the hoop stresses have values which are 1.5–2 times higher than the longitudinal stresses. From the point of view of the structural design of the container, the hoop stress is thus a more critical measure.

Figs.8 and 9 illustrate the variation in the maximum longitudinal stress along the length of the container. These compressive stresses reach a peak at the level of the discontinuity. It is also shown that stress distributions predicted from the analyses which utilize non-linear modelling of soil behaviour are substantially higher than those calculated by assuming linear elastic behaviour of the soil. In all cases, the variation of stress around the region of the discontinuity is very abrupt. Figs.10 and 11 show the circumferential distribution of hoop stresses at levels where the corresponding maximum values occur. In all cases, the stresses change from compressive to tensile to

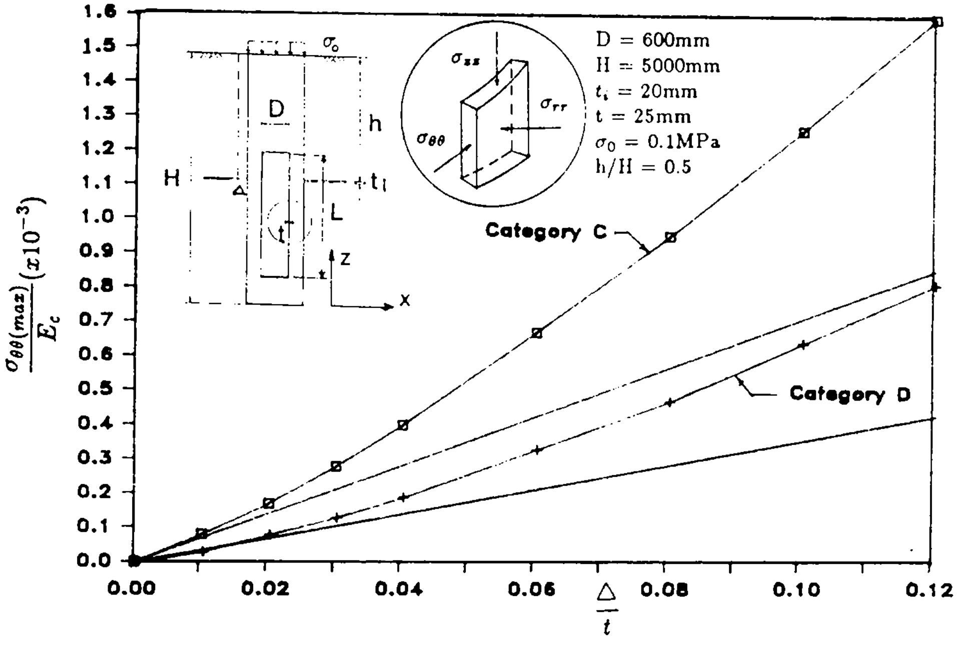

Fig.6. Maximum hoop stress vs. displacement ($E_c/E_b = 2000$).

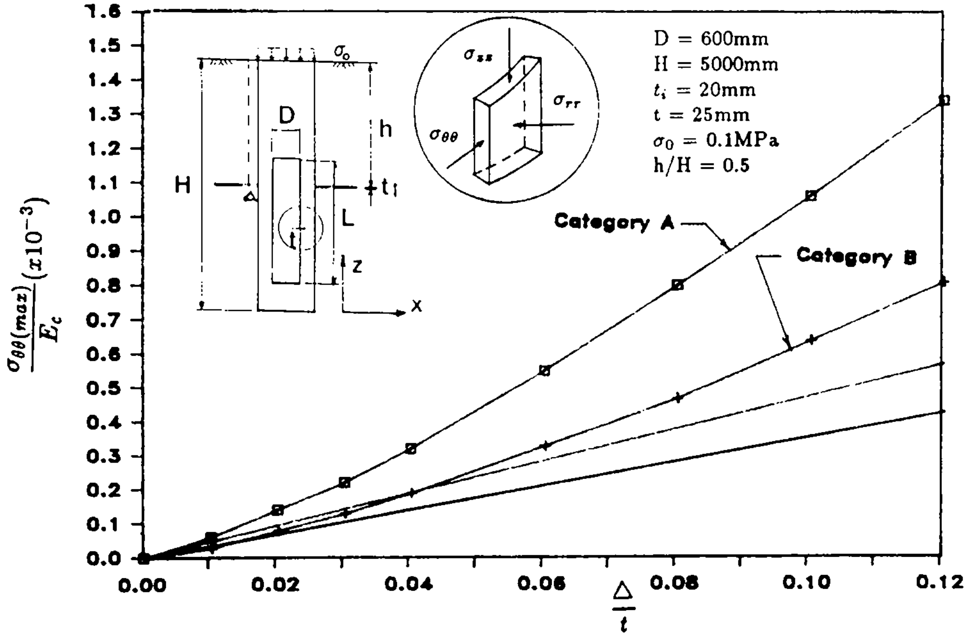

Fig.7. Maximum hoop stress vs. displacement ($E_c/E_b = 700$).

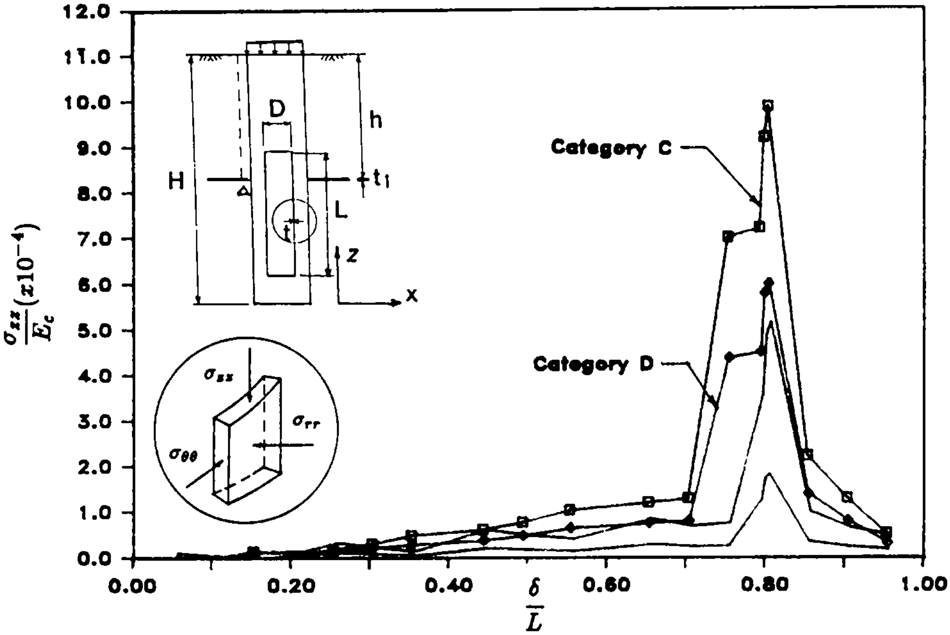

Fig.8. Longitudinal stress distribution along container ($\Delta/D = 6.0 \times 10^{-3}$).

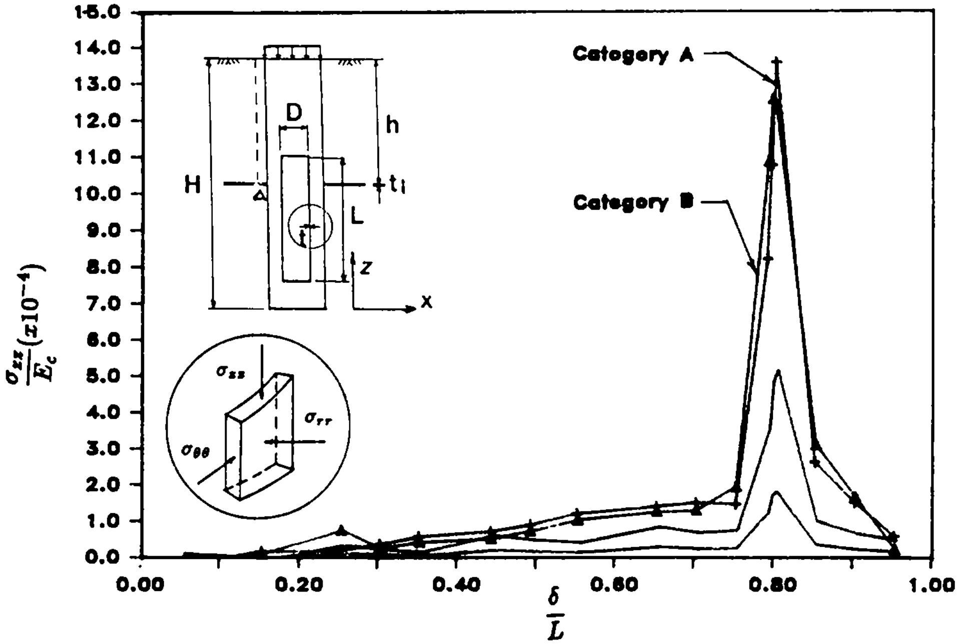

Fig.9. Longitudinal stress distribution along container ($\Delta/D = 6.0 \times 10^{-3}$).

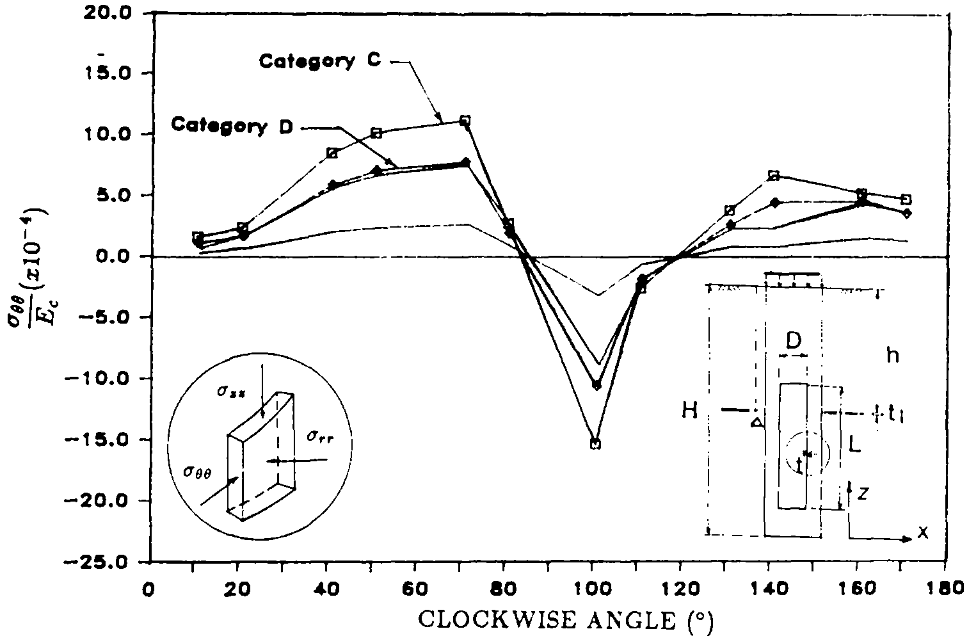

Fig.10. Circumferential hoop stress distribution ($\Delta/D = 6.0 \times 10^{-3}$).

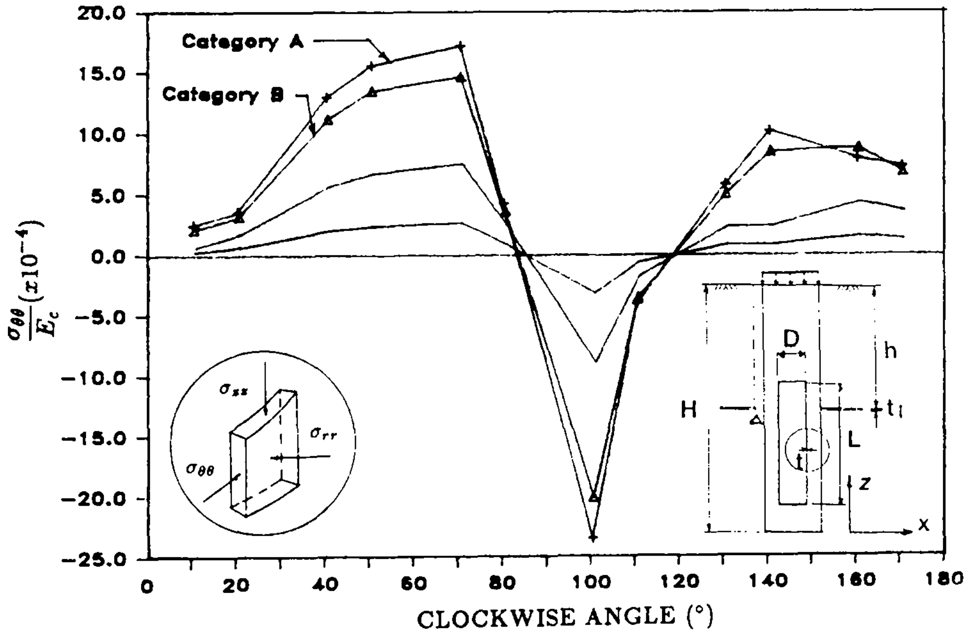

Fig.11. Circumferential hoop stress distribution ($\Delta/D = 6.0 \times 10^{-3}$).

compressive. Also, the tensile stresses are larger than the compressive stresses. These stress distributions point to the fact that the container shell undergoes contra-flexural bending along the circumferential direction during the discontinuous rock movement.

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