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Nonlinear explicit analysis and study of the behaviour of a new ring-type brake energy dissipator by FEM and experimental comparison

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ABSTRACT

The aim of this paper is to comprehensively analyse the performance of a new ring-type brake energy dissipator through the finite element method (FEM) (formulation and finite element approximation of contact in nonlinear mechanics) and experimental comparison. This new structural device is used as a system component in rockfall barriers and fences and it is composed of steel bearing ropes, bent pipes and aluminium compression sleeves. The bearing ropes are guided through pipes bent into double-loops and held by compression sleeves. These elements work as brake rings. In important events the brake rings contract and so dissipate residual energy out of the ring net, without damaging the ropes. The rope's breaking load is not diminished by activation of the brake. The full understanding of this problem implies the simultaneous study of three nonlinearities: material nonlinearity (plastic behaviour) and failure criteria, large displacements (geometric nonlinearity) and friction-contact phenomena among brake ring components. The explicit dynamic analysis procedure is carried out by means of the implementation of an explicit integration rule together with the use of diagonal element mass matrices. The equations of motion for the brake ring are integrated using the explicit central difference integration rule. The presence of the contact phenomenon implies the existence of inequality constraints. The conditions for normal contact are $\lambda \geqslant 0$, $g \geqslant 0$ and $g\lambda = 0$, where λ is the normal traction component and g is the gap function for the contact surface pair. To include frictional conditions, let us assume that Coulomb's law of friction holds pointwise on the different contact surfaces, μ being the dynamic coefficient of friction. Next, we define the non-dimensional variable τ by means of the expression $\tau = t/\mu\lambda$, where $\mu\lambda$ is the frictional resistance and t is the tangential traction component. In order to find the best brake performance, different dynamic friction coefficients corresponding to the pressures of the compression sleeves have been adopted and simulated numerically by FEM and then we have compared them with the results from full-scale experimental tests. Finally, the most important conclusions of this study are given.

1. Introduction

The finite element method is a numerical procedure that can be used to obtain solutions to many engineering problems involving stress analysis, heat transfer, electromagnetism, and in our case, a new ring-type brake energy dissipator [1–6].

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The main objective of this paper is to determine by FEM the absorbed energy and the failure modes in the different components of the brake. Then the FEM results are compared with experimental ones obtained by means of full-scale tests.

The bearing ropes are guided through pipes bent into double-loops and held by compression sleeves forming elements that work as brake rings. In large events the brake rings contract and so dissipate the residual energy out of the ring net, without damaging the ropes (see Fig. 1).

The falling rock protection system consists of a product made of nets [4] (interception structure), posts (support structure), ropes (connection structure) and brakes (connection structure). The energy level of a falling rock protection kit is defined as the kinetic energy of a regular block impacting on the net fence. In this way, the energy dissipating device is the most important element in order to absorb energy and to avoid the rupture of the connection components, so that the complete separation occurs of the component itself into two distinct parts.

2. Strong form of the initial boundary value problem

An elastoplastic body occupies a bounded domain $\Omega \subset \Re^d (d = 2, 3)$ with a Lipschitz boundary Γ, partitioned into three disjointed measurable parts Γ_u, Γ_σ and Γ_c so that $meas(\Gamma_u) > 0$ [7]. A volume force of density $\vec{f}^B$ acts in Ω and a surface traction of density $\vec{f}^S$ acts on Γ_σ. The body is clamped on Γ_u and thus the displacement and velocity fields vanish there. On Γ_c the body is in contact with other bodies, the so-called compression sleeves, bearing ropes and pipe bends. We model the contact with Coulomb's law of dry friction [5,8,9]. Finally, M_d denotes the space of the second-order symmetric tensors on $\Re^d$, or equivalently, the space of the symmetric matrices of order d.

The strong formulation of the contact problem is the following:

Problem 1. For all $t \in I[0, T]$and all $\vec{x} \in \Omega$, find a displacement field $\vec{u}(\vec{x}, t) : \Omega \times [0, T] \to \Re^d$ and a stress field $\vec{\sigma}(\vec{x}, t) : \Omega \times [0, T] \to M_d$ so that they satisfy [10]:

1. Linear momentum balance:

$$\nabla \cdot \vec{\sigma} + \vec{f}^B = \rho \ddot{\vec{u}} \tag{1}$$

in direct notation and

$$\sigma_{ij,j} + f_i^B = \rho \ddot{u}_i \tag{2}$$

in indicial notation. In Eqs. (1) and (2), $\vec{\sigma}$ is the Cauchy stress tensor, σ_{ij}, f_i^B being the components of the applied body force per unit volume $\vec{f}^B$, and the scalar ρ denotes the mass density, which may in general depend on the coordinates $\vec{x} \in \Omega$. The two superposed dots on $\vec{u}$ denote partial differentiation with respect to time twice. The notation j in a subscript indicates partial differentiation of the quantity with respect to that coordinate direction.

2. Initial and boundary conditions: In addition to the previous momentum balance, which must hold for any time $t \in I[0, T]$, the problem is in general subject to certain initial and boundary conditions as well. The boundary conditions are stated by introducing prescribed tractions $\bar{\vec{f}}^S : \Gamma_\sigma \times [0, T] \to \Re^d$ and prescribed displacements $\bar{\vec{u}} : \Gamma_u \times [0, T] \to \Re^d$ and requiring:

$$\sigma_{ij} n_j = \bar{f}_i^S \text{ for all } \vec{x} \in \Gamma_\sigma, \quad t \in [0, T] \tag{3}$$

$$u_i = \bar{u}_i \text{ for all } \vec{x} \in \Gamma_u, \quad t \in [0, T] \tag{4}$$

where n_j refers to the components of the outward normal $\vec{n}$ to Γ_σ. Initial conditions may be expressed by introducing an initial displacement field $\vec{u}_0 : \bar{\Omega} \to \Re^d$ and initial velocity field $\vec{v}_0 : \bar{\Omega} \to \Re^d$ where $\bar{\Omega}$ denotes the closure of the open set Ω; that is to say, including the boundary $\partial\Omega = \Gamma_u \cup \Gamma_\sigma \cup \Gamma_c$, and requiring:

$$u_i|_{t=0} = u_{0i} \quad \text{in } \bar{\Omega}, \tag{5}$$

$$\dot{u}_i|_{t=0} = v_{0i} \quad \text{in } \bar{\Omega} \tag{6}$$

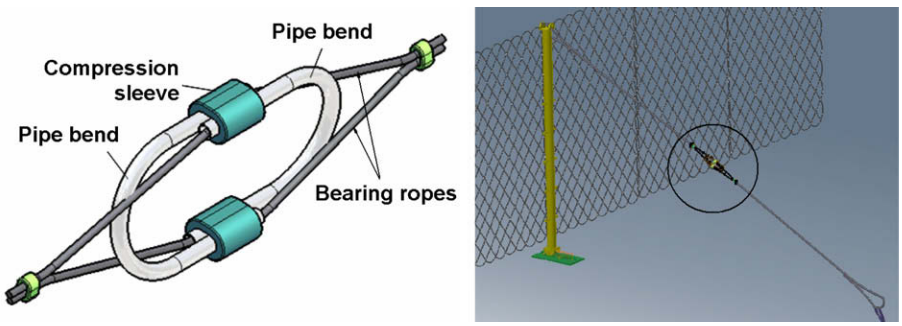

Fig. 1. Geometrical model of the new ring-type brake dissipator (left) and falling rock protection system (right).