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Mechanical characterisation and strain rate sensitivity of rubber shockpad in 3G artificial turf

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ABSTRACT

Artificial turf systems are increasingly prolific, and are typically comprised of multi-components. Their responses to interactions with users and equipment can be relatively complex under different loading conditions as they tend to be polymeric and elastomeric and hence can exhibit non-linear and strain rate dependent behaviour. To further study and better understand the behaviour of these systems, the development of a numerical model to accurately predict individual layers' behaviour as well as the overall system's response under different loading conditions is necessary. Such a model can be used to better optimise surface design such as material choices and layer thickness, also possibly reducing construction costs. The purpose of this study was to model the mechanical behaviour of the rubber shockpad layer used in 3G artificial turfs using finite element (FE) analyses. Shockpad layers in artificial turf play a vital role in the shock absorption and ball interactions, and affect user safety. The rubber shockpad used in this study was an elastic prefabricated mat comprised of recycled rubber shreds approximately 2 to 8 mm in size bonded with polyurethane.

A series of 3D finite element dynamic analyses were carried out using ABAQUS applying compressive cyclic loading to simulate the shockpad behaviour under different loading frequencies. The frequencies were based on biomechanical data for an athlete walking, running and sprinting. Arruda-Boyce hyperelastic constitutive model was employed to best describe the stress-strain response of the rubber shockpad under compressive loading. A series of uniaxial compression tests were conducted and the results were employed to characterise the mechanical behaviour of the material. The best Arruda-Boyce's coefficients, for different strain rates were obtained using initial estimation (IEM) method and trial-and-error approach. The FE results showed the best-fit hyperelastic material model which can describe and predict the material behaviour under various strain rates. Finally, using finite element results a series of models were proposed to accurately predict the stress-strain behaviour of the material in different loading frequencies relevant to athlete.

Keywords: *Rubber shockpad, Finite element modelling, Hyperelastic, ABAQUS, Mechanical Properties.*

1. Introduction

Third generation (3G) artificial turf was developed in the late 1990s, and designed to better simulate natural turf [7]. Most of 3G turf surfaces have a similar structure comprising the key components of an artificial carpet, a shockpad layer and an engineered aggregate foundation (Fig 1). Shockpad layer creates desired playing characteristics for the particular sport in addition to maintain the initial qualities of the artificial pitches during their service life. There are three types of shockpads on the market: integral shockpad, in-situ and prefabricated [6]. Cast in-situ shockpads are constructed from recycled rubber particles bonded together using polyurethane binder. Design and mechanical features of the prefabricated shockpads are very similar to the in-situ type; however, the prefabricated shockpads are manufactured in factories based on specific requirements. Their significant advantage is the uniformity of their mechanical properties and thickness as a result of the controlled construction environment. The principal force applied to a shockpad layer in artificial turf systems is mainly vertically compressive. Physical and mechanical behaviour of rubber-like material when subjected to compressive loading have been investigated by different researchers using experimental, analytical and numerical studies [10]. Thomson et al. [8] attempted to create a finite element model (FEM) of experimentally measured quasi-static response of a particular treadmill surface made of flexible rubber mat under compressive loading using ABAQUS. Song et al. [2] assessed the strain rate dependency of ethylene–propylene–diene monomer (EPDM) rubber for a range of 0.0015 to 4700 s^{-1} and concluded rubber becomes increasingly non-linear by increasing strain rate. Andena et al.

[5] studied the possibility of predicting the force reduction (FR) and shock absorbing capability of running tracks using ABAQUS software. However, no studies have looked at different components of 3G artificial turfs in particular their behaviour under complex dynamic loading conditions.

The purpose of the present study was to investigate the mechanical characterisation and strain rate dependency of rubber shockpad layer used in third generation artificial turf using finite element method. To that end, the mechanical response of the material under various loading frequency were characterised by a series of uniaxial compression tests and then Arruda-Boyce's hyperelastic model which is already implemented into ABAQUS was selected to fit the experiments. Arruda-Boyce's parameters were estimated firstly using an initial estimation method (IEM) and subsequently improved by trial-and-error approach. Finally, based on the finite element analyses, a series of equations were proposed combining the Arruda-Boyce's material model parameters with a new parameter to consider strain rate dependency of the material behaviour for various loading frequencies ranging between 0.9 to 10 Hz.

2. Material characterisation and compression test

The shockpad used in this study was an elastic premanufactured mat made from rubber aggregates bonded with polyurethane. The rubber particles were graded ranging between 2 to 8 mm, and the average density of the rubber shockpad was 557 kg/m^3. The uniaxial compression behaviour of the material under different cyclic loading frequencies (0.9, 3.3 Hz and 10 Hz) relevant to athlete walking, running and sprinting was measured using electropuls instron compression machine. The peak vertical impact force for all dynamic cyclic loadings was controlled within the range of 1800N±15%. This load was applied by a cicular loading feet (50 mm diameter) to simulate a shod adult's heel [10].

3. Model geometry and mesh

To achieve precise results, three-dimensional finite element analyses of above experiments were carried out using ABAQUS. Taking advantage of the symmetrical nature of the problem, only a quarter of the entire system was modelled. Figure 2 represents the typical finite element mesh for the rubber shockpad layer, used in this study. A number of different mesh densities in which element sizes around and under the loading area are refined were performed to obtain accurate results in a reasonable computational time. The mesh is extended 5B (B=50mm is the diameter of loading area) from the layer centre line. Boundary conditions were defined according to the adopted experimental condition. In order to model the rubber, first-order, eight-node linear brick, reduced integration with hourglass control element (C3D8R) was employed.

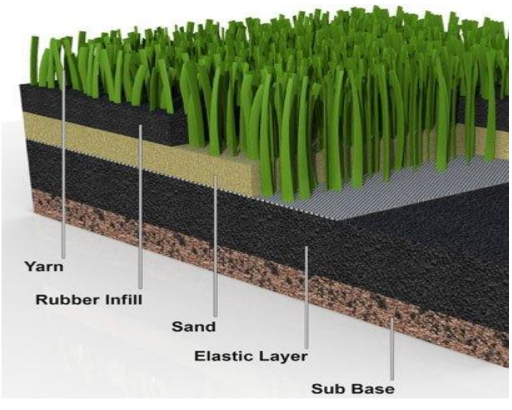

Figure 1: Schematic of a 3G artificial turf system [11]

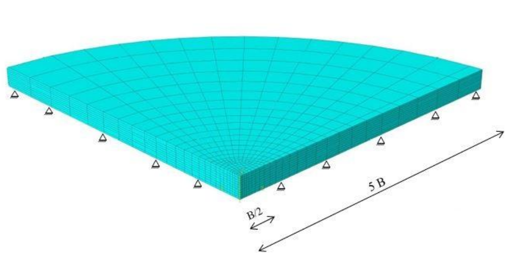

Figure 2: finite element mesh and boundary conditions

4. Constitutive hyperelastic modelling

Generally, rubber like material can exhibit instantaneous elastic response up to large strains without permanent set, and are defined by stored energy function as hyperelastic material. In this paper, the 8-chain Arruda-Boyce hyperelastic constitutive model including compressibility has been selected to simulate rubber shockpad behaviour under various dynamic loading conditions. Arruda-Boyce constitutive model has been preferred because it has been shown to accurately capture the large strain equilibrium response of several types of elastomers [4], and it is the most successful expression of a strain energy function using the non-Gaussian method of the statistical molecular theory [3]. The form of Arruda-Boyce strain energy potential in fifth order approximation is expressed as following [9]:

$$W = \mu \sum_{i=1}^{5} \frac{Ci}{\lambda_m^{2i-2}} (I_1^{'i} - 3^i) + \frac{1}{D}(\frac{J^2 - 1}{2} - \ln J) \qquad (1)$$

where I_1 and J are the first deviatoric strain invariant and the elastic volume ratio respectively; and

$$\mu = \mu_0 (1 + \frac{3}{5\lambda_m^2} + \frac{99}{175\lambda_m^4} + \frac{513}{875\lambda_m^6} + \frac{42039}{67375\lambda_m^8})^{-1} \qquad (2)$$

$$C_1 = \frac{1}{2}, C_2 = \frac{1}{20}, C_3 = \frac{11}{1050}, C_4 = \frac{19}{7000}, C_5 = \frac{519}{673750} \qquad D = \frac{2}{k_0}$$

in this formulation, μ_0 and k_0 are the initial shear and bulk modulus of the material, and λ_m is the locking stretch.

5. Material parameters determination

The difficulty of hyperelastic material models is determination of the coefficients in their functions which should be determined via experiments. On the other hand, hyperelastic models should be combined with a rate dependent model to demonstrate the strain rate dependency trait of rubber, since the experimental results revealed strain rate dependency behaviour of the material even at low strains (Fig 3). The large strain uniaxial compression test results were employed to estimate an initial value for the Young's modulus (E_0) as well as the locking stretch (λ_m) of the material for each frequency. Poisson's ratio of the material is also required for initial estimation of D and μ_0 and it cannot be determined from a uniaxial compression test. Using the proposed value for initial Poisson's ratio of rubber particles approximately 2 to 10 mm in size, ρ=585kg/m^3 and porosity, i.e. n = 49%, an initial Poisson's ratio about 0.3 was adopted [1]. This initial estimation method (IEM) for determining Arruda-Boyce's parameters prevents extra effort to find appropriate material parameters to be implemented in ABAQUS. The linear elastic part (initial slope) of the stress-strain curve (Fig 3) can determine approximate value of initial Young's modulus (E_0), and initial approximation of λ_m can be obtained from the following formulation [4]:

$$\lambda_m = \sqrt{\frac{1}{3}(\lambda_l^2 + \frac{2}{\lambda_l})} \qquad (3)$$

in which λ_l is the stretch when the stress increases without any further significant changes in the strain (Fig 3).

6. Finite element analyses results

Firstly, a series of dynamic FE models were created in which the material parameters were calculated and implemented into ABAQUS based on IEM predictions. All finite element simulations were conducted by applying compressive loads on the same loading area as in the experiments. The finite element results based on IEM's predictions for Arruda-Boyce's coefficients showed an acceptable prediction for stress-strain behaviour, however in order to achieve the best agreement between the FEA results and experimental data, trial and error approach was utilised to improve the material parameters as suggested. The results of numerical simulations and experimental data are presented in Fig 3. It should be noted that the excellent agreement between experimental and FE results simply confirms the choice of a suitable model, since the experimental results were used to define the input parameters to the FE analysis. Using the obtained values for Arruda-Boyce's coefficients (μ, λm and D) a series of equations are proposed to take into account the strain rate dependency of material which is an essential characteristic of the material behaviour. The proposed equations cover the 0.9 – 10 Hz frequency range.

$$\mu = 107.25 \times 10^3 f^{0.295} \qquad D = 3 \times 10^{-9} f^2 - 9 \times 10^{-8} f + 2.7 \times 10^{-6} \qquad \lambda_m = 1.0152 f^{0.0587} \qquad (4)$$

In which f is frequency, and the unit of μ and D are Pa(N/m^2) and Pa^{-1} respectively.

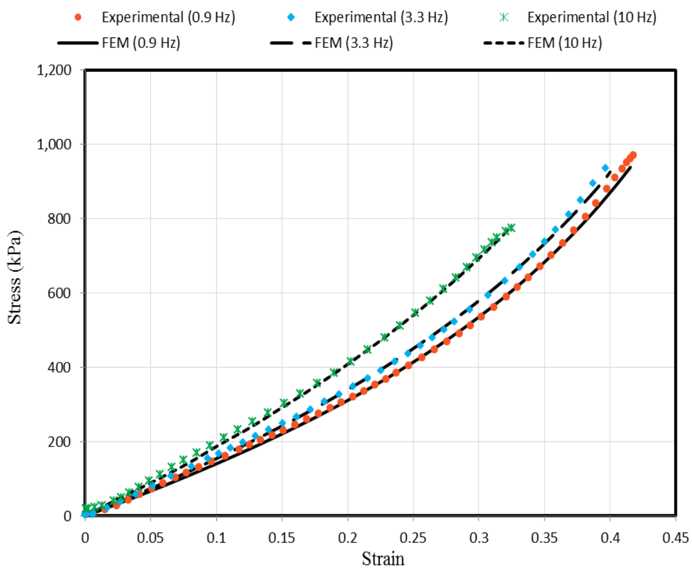

Figure 3: Comparison between FE results and experimental data for 0.9, 3.3 and 10 Hz loading frequency

7. Summary and conclusions

In this paper a series of finite element models are developed to study the behaviour of rubber shockpad layer under dynamic compression loading. A hyperelastic material model, i.e. Arruda-Boyce was adapted to simulate the constitutive behaviour of the shockpad. The results of the FE simulations were used to propose a model to predict the strain rate dependent material behaviour. This model combines the existing Arruda-Boyce's parameters with an additional parameter, i.e. load-frequency, to describe strain rate sensitivity of the material under different loading rate. The proposed new model, once implemented in FE, will enhance the accuracy and capability of the future FE analyses hence improving our understanding and design of such materials.

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