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

Moura Mehravar 1*, Paul Fleming 2, David Cole 1, Steph Forrester 1

1Wolfson School of Mechanical, Manufacturing and Electrical Engineering, Loughborough University, UK
2School of Civil and Building Engineering, Loughborough University, UK

*M.Mehravar@lboro.ac.uk

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/m³. 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.

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]:
\[
W = \mu \sum_{i=1}^{6} \frac{\alpha_i}{\lambda_m^2} (I_i^3 - 1) + \frac{1}{D} \left( \frac{J^2 - 1}{2} - \ln J \right)
\]
(1)

where \(I_i\) and \(J\) are the first deviatoric strain invariant and the elastic volume ratio respectively; and
\[
\mu = \mu_0 (1 + \frac{3}{5} \frac{\lambda_m}{\lambda_m^3} + \frac{99}{875} \frac{\lambda_m^2}{\lambda_m^5} + \frac{513}{67375} \frac{\lambda_m}{\lambda_m^5} + \frac{42039}{673750})^{-1}
\]
(2)
\[
C_1 = \frac{1}{2}, C_2 = \frac{1}{20}, C_3 = \frac{11}{1050}, C_4 = \frac{19}{7000}, C_5 = \frac{519}{673750}, D = \frac{2}{k_0}
\]

in this formulation, \(\mu_0\) and \(k_0\) are the initial shear and bulk modulus of the material, and \(\lambda_m\) 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 \((\lambda_m)\) of the material for each frequency.

Poisson’s ratio of the material is also required for initial estimation of \(D\) and \(\mu_0\) 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, \(\rho=585\text{kg/m}^3\) 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 \(\lambda_m\) can be
obtained from the following formulation [4]:

\[
\lambda_m = \sqrt[3]{\frac{1}{3} \left( \lambda_1^2 + \frac{2}{\lambda_1} \right)}
\]
(3)
in which \(\lambda_1\) 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 \((\mu, \lambda_m \text{ and } D)\) 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.

\[
\mu = 107.25 \times 10^3 f^{-0.295} \quad D = 3 \times 10^{-9} f^2 - 9 \times 10^{-8} f + 2.7 \times 10^{-6} \quad \lambda_m = 1.0152 f^{0.087}
\]
(4)
In which $f$ is frequency, and the unit of $\mu$ and $D$ are $\text{Pa(N/m}^2\text{)}$ and $\text{Pa}^{-1}$ respectively.

![Graph showing comparison between FE results and experimental data for 0.9, 3.3 and 10 Hz loading frequency](image)

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.

References


