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# Viscoelastic modelling of tennis ball properties

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# Viscoelastic Modelling of Tennis Ball Properties

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**Abstract**. An explicit finite element (FE) tennis ball model which illustrates the effects of the viscoelastic materials of a tennis ball on ball deformation and bounce during normal impacts is presented. A tennis ball is composed of a rubber core and a fabric cover comprised of a wool-nylon mix which exhibit non-linear strain rate properties during high velocity impacts. The rubber core model was developed and validated using low strain rate tensile tests on rubber samples as well as high velocity normal impacts of pressurised cores at velocities ranging from 15 m/s to 50 m/s. The impacts were recorded using a high speed video (HSV) camera to determine deformation, impact time and coefficient of restitution (COR). The material properties of the core model were tuned to match the HSV results. A two component anisotropic fabric model was created which included artificial Rayleigh damping to account for hysteresis effects, and the core model 'tuning' process was used to refine the cloth layer. The ball model's parameters were in good agreement with experimental data at all velocities for both cores and complete balls, and a time sequenced comparison of HSV ball motion and FE model confirmed the validity of the model.

## 1. Introduction

The early game of tennis, called real tennis, originated in France in the 13th century and balls were made of wool covered with sheepskin. The game became so popular that a few hundred years later, the king Henry IV defined standards for the manufacturing of balls which had to be covered with white cloth and stuffed with strips of cloth tied with thread [1]. It is not until 1873 that Major Wingfield introduced lawn tennis which is the closest version of today's tennis, and the manufacturing process of tennis balls has barely changed since then.

Three types of tennis balls including harder fast-speed balls for slow surfaces and larger slow-speed balls for fast surfaces are currently allowed by the International Tennis Federation [2], but the main balls used in professional championships are regular pressurised tennis balls, also called Type 2 balls. These balls consist of a rubber core covered by two dumbbell shaped pieces of cloth which are made of wool and nylon fibres in the weft direction and cotton fibres in the warp direction. During the manufacturing process, each dumbbell is cut from a large sheet of fabric at a 45 degree angle relative to the fibres' orientation to facilitate the application of the cloth on the core. The dumbbells are dipped into a rubber sealing solution and are semi-automatically applied to the cores. The balls are then heated into a press to cure the rubber solution, finish curing the core, and smoothen the seam formed by the excess rubber sealing solution after application of the dumbbells on the core. Finally, the ball goes through a steaming process to raise the cloth fibres and give it a fluffy aspect.

 

The combination of these manufacturing characteristics together with the use of strain rate dependent materials result in complex ball behaviour during high velocity impacts, and finite element (FE) methods have often been used to better understand the mechanisms involved in sports ball impacts. Ismail and Stronge [3] and Tanaka *et al.* [4] developed FE models of golf ball impacts which included hyperelastic and viscoelastic material definitions, and both simulations were in good agreement with experimental results. Price [5] developed a soccer ball FE model in which the bladder was modelled as a hyperelastic material with viscoelastic components based on dynamic mechanical analysis (DMA) measurements. Price also introduced an anisotropic material definition and the model was validated using high speed video camera (HSV) data. Cordingley [6] and Allen *et al.* [7] presented FE models of tennis ball impacts in which both core and cloth were modelled using isotropic material definitions. Cordingley used a hyperelastic material definition for the core, and the energy loss and strain rate dependency due to the viscoelastic nature of the rubber were taken into account by introducing artificial damping and tuning the material properties of the core to match HSV results. Both Cordingley [6] and Allen *et al.* [7] assumed the cloth to be subjected mainly to compression forces during the impact, and both models used a hyperfoam definition to model the cloth, therefore neglecting its tensile behaviour. Parameters such as coefficient of restitution (COR) or impact time were in good agreement with experimental results at low speeds, however, errors up to 25% in the ball maximum deformation values were observed when compared with HSV results.

Most of these ball impact simulations, except Price's soccer ball impact, were modelled using isotropic material characterisations. This study expands on Cordingley's work and takes a step further in the modelling of tennis ball impacts by introducing the anisotropic behaviour of the tennis ball cloth, therefore allowing for a better understanding of the effects of the viscoelastic properties of the rubber and cloth on ball deformation during high velocity impacts.

## 2. Core Finite Element (FE) Model

This section details the development of the rubber core FE model created in ABAQUS/explicit. The core was assumed to be homogeneous and isotropic as the seam formed by the assembly of the two half shells was experimentally found to have no significant effect on the core's behaviour during high velocity impacts.

### *2.1. Core Mesh*

The core model consists of a total of 5760 first order reduced integration triangular solid elements arranged in two layers and in a spherical icosahedral mesh. The spherical icosahedron was found to be the appropriate geometry for the mesh production because it exhibits rotational symmetry as well as high levels of uniform impact characteristics [5, 6]. A membrane of two dimensional hydrostatic elements sharing nodes with the triangular solid elements was added in the interior surface of the sphere allowing a coupling between pressurisation of the fluid elements and the material response associated with the solid elements. All the hydrostatic elements also shared a common node, known as the reference cavity node, having a single degree of freedom representing the pressure inside the cavity. The core was filled with a compressible fluid following the ideal gas low, and a pressure of 83 kPa was uniformly applied inside the cavity as an initial condition.

### *2.2. Core Material Properties*

Although tennis balls are subjected to very high strain rates during professional play, the rubber core material model requires the quasi-static stress-strain behaviour of the rubber to be determined experimentally. Tensile tests at 200 mm/min and 500 mm/min were performed on rubber dogbone samples of Type I (ISO 37) directly cut out from the cores using an Instron material testing machine. A preload of 1 Newton was applied on each test specimen to remove the initial bend due to the core curvature, and all specimen were stretched up to a strain of 0.5. Figure 1 shows that although the specimen were tested at different strain rates, they exhibit the same linear load-extension curves, indicating that the strain rate dependency of rubber, characteristic of its viscoelastic behaviour, is not really observable for small strains at low strain rates.

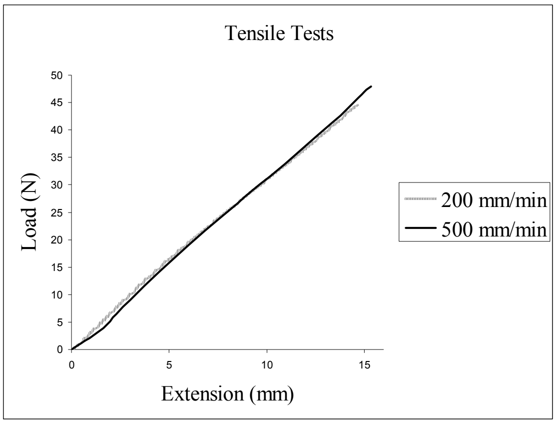


**Figure 1.** Comparison of specimens tested at 200 mm/min and 500 mm/min.

Tennis balls are subjected to strain rates almost 2000 times higher than the maximum strain rate of most standard tensile test machines, however, the data obtained from the low strain rate tensile tests were input into the FE software and used as a basis for the rubber core material model.

*2.3. Core Material Model and Model Validation*

When test data are used, the software compares all the different strain energy potentials with experimental data and calibrates the material coefficients for each model [8]. A hyperelastic material model with a reduced polynomial strain energy potential gave the best fit when compared with the test data obtained from the low strain rate tensile tests and was therefore chosen to model the rubber. Previous work in the field of ball impacts [5, 6] also used this material model and it proved to be accurate enough with errors lower than 5%. The rubber was given a density of about 1500 kg/m$^3$, and the ratio of the rubber core's initial bulk modulus to its initial shear modulus was defined by a Poisson's ratio default value of approximately 0.5. However, the material properties are highly affected by the velocity of the impact, and the rubber stiffness and energy loss increase with increasing inbound velocity. Cross [9] studied the difference between slow and fast compressions and showed that the hysteresis was much larger for the fast compression case. The reason for a larger energy loss is that the ball buckles later and at a higher load than during slow compression and therefore the ball loses more of its stored elastic energy during fast compression. Since the hyperelastic material models in Abaqus do not account for energy losses, an artificial Rayleigh damping was introduced in the model, and the stiffness and damping of the model could then be tuned to match experimental high speed video (HSV) results.

In order to correctly tune the core material model properties, high velocity impacts of pressurised cores were recorded using a HSV camera at a rate of 10000 frames per second. A light gate was used to measure the inbound velocity which ranged from 15 m/s up to 50 m/s. The recorded images were then analysed using Image Pro software, a commercial image processing package, and COR, impact time and horizontal and vertical deformation (as defined in figure 2) were measured. The material model properties were then tuned until COR, impact time and deformation values were within 5% of the values obtained experimentally. Figure 3 shows the difference between the stress-strain curves from the low strain rate test data and the tuned model data. It can be seen that the elastic modulus of the cores is much higher at high strain rate than at low strain rate.

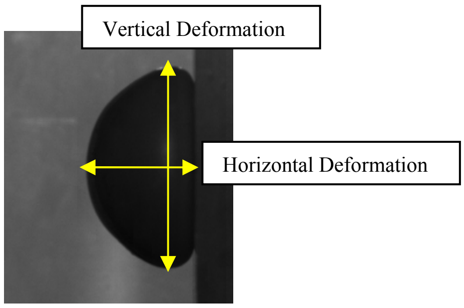


**Figure 2.** Maximum ball deformation during impact.

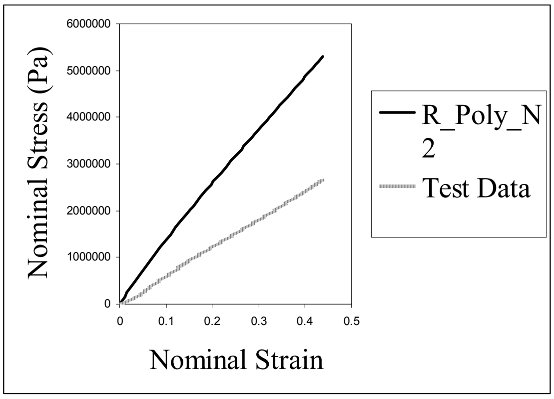


**Figure 3.** Stress-strain curves of the final material model and the test data at a strain rate of 500 mm/min.

The comparison between simulation and experimental impacts is shown in figures 4 to 7, and the model data fell within 5% of the experimental results for all velocities. Therefore, the core model was validated for all speeds from 15 m/s to 50 m/s. As seen on these figures, increasing the inbound velocity results in a decrease in the COR, impact time and horizontal deformation, whereas the vertical deformation increases with increasing velocity.

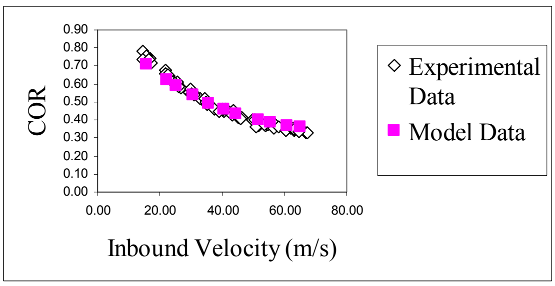


**Figure 4.** COR values for model and experimental data.

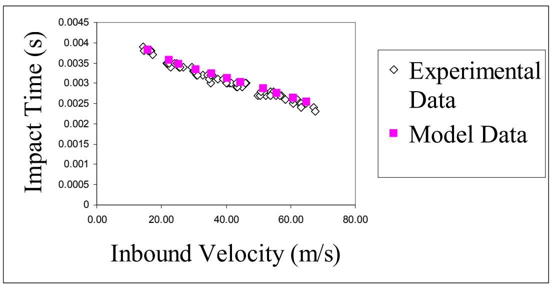


**Figure 5.** Impact time values for model and experimental data.

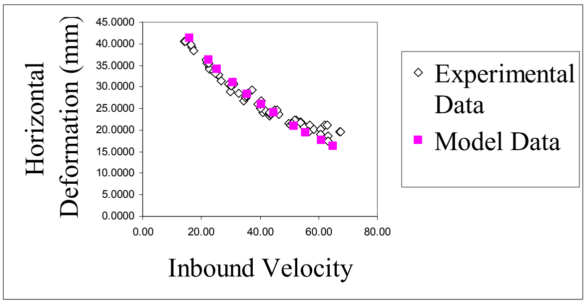


**Figure 6.** Horizontal deformation values for model and experimental data.

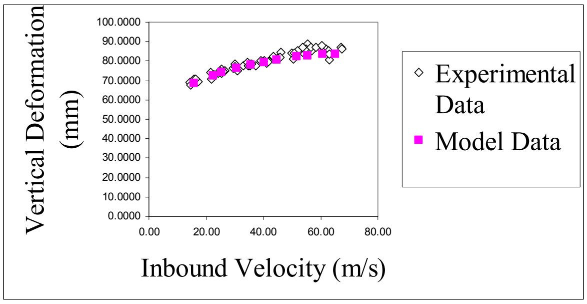


**Figure 7.** Vertical deformation values for model and experimental data.

## 3. Cloth Covered Ball Finite Element (FE) Model

This section describes the development of the complete ball model that includes the anisotropic behaviour of the cloth due to the different fibres. A technique for carpet modelling in car crash test simulations consists in using shell elements to model the tensile load carrying capacity of the carpet, and brick elements to represent the compressibility of the carpet [10]. A similar technique was used to model the cloth.

### *3.1. Cloth Mesh*

As mentioned previously, tennis ball cloth is a highly anisotropic material and behaves quite differently during compressive and tensile loading, and in order to model both behaviours accurately, the cloth was divided into two layers with different material properties. The anisotropic behaviour of the woven backing fibres was modelled using a layer of 2392 linear quadrilateral shell elements having material directionality properties oriented at a 45 degree angle relative to the cloth seam, as shown in figure 8. The compressive behaviour of the raised fibres, or 'fuzz', was assumed to be isotropic and was modelled with the icosahedral mesh previously used for the core. A tie constraint was then used to tie the layers together and tie the cloth to the core.

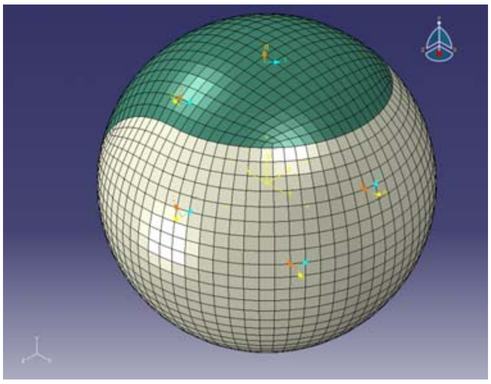

**Figure 8.** Dumbbells with arrows showing material directionality

### *3.2. Cloth Material Properties*

In order to evaluate the anisotropic properties of the cloth, tensile tests were performed on cloth specimens (50mm x 100mm x 3mm) with fibres oriented at nine different angles, from 0 degrees to 90 degrees relative to the cotton fibres. Each specimen was tested at two different strain rates, 100 mm/min and 500 mm/min, to assess the effect of strain rate on cloth deformation. A preload of 10 Newton was applied on each specimen. The test results are presented in figures 9 and 10. Figure 9 shows the variation of Young's modulus in function of fibres' orientation. The specimens stretched along the wool and nylon fibres (90 degrees) appear to be much more elastic than the specimens tested along the cotton fibres (0 degrees). The low Young's modulus value at 45 degrees is due to the fibres sliding about their crossover points during stretching. It should be noted that these results correspond to a cloth thickness of only 1 mm instead of the usual 3 mm since it was considered that the tensile load was carried mainly by the woven fibres. This modification was needed to incorporate the results in the FE model in which the shell elements chosen to represent the tensile behaviour of the cloth were given a thickness of 1 mm. Figure 10 shows that the cloth is strain rate dependent as a higher strain rate results in a stiffer cloth. Therefore, the cloth was qualified as being anisotropic and viscoelastic, two characteristics that were taken into account in the FE ball modelling.

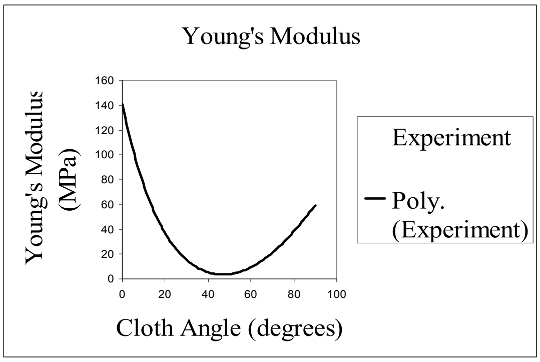


**Figure 9.** Young's modulus in function of cloth orientation for a constant strain of 0.1.

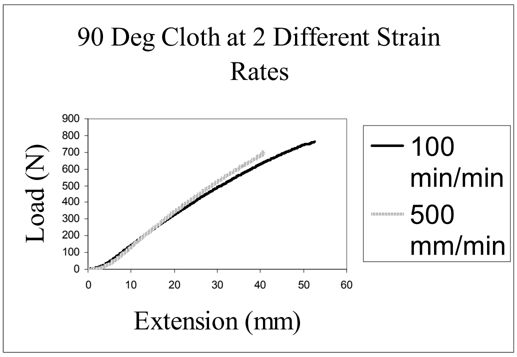


**Figure 10.** Cloth strain rate dependency.

The compressibility of the cloth was tested through compression tests performed at a strain rate of 200 mm/min. Cylindrical cloth specimens with a 50 mm diameter were created by stacking five layers of cloth together resulting in a thickness of 17 mm (3 mm per cloth layer plus the glue layers). The test results are shown in figure 11, and it can be seen that the cloth is subjected to a very large deformation during the initial phase, probably due to the compression of the raised fibres, followed by a much stiffer behaviour attributed to the compression of the woven backing layer. It should be noted that the compression tests were performed on specimens composed of the woven backing layer and raised fibres since it would have been very difficult to perform compression tests on the raised fibres only.

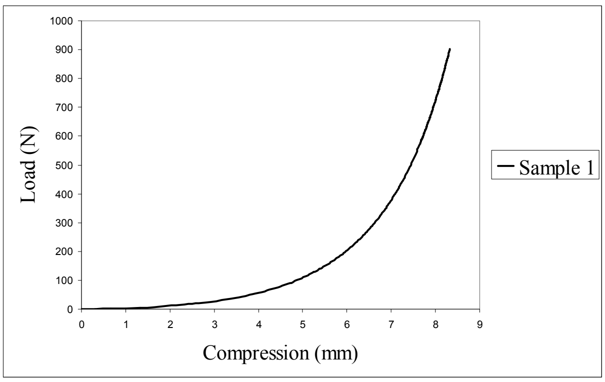


**Figure 11.** Compression tests on a cloth specimen.

### *3.3. Cloth Material Model and Complete Ball Model Validation*

The tensile behaviour of the cloth was modelled using a plane stress orthotropic elastic material definition which includes the variation of the cloth stiffness in function of the fibres' orientation. The compressive behaviour of the cloth was modelled using a hyperelastic reduced polynomial material definition. These models were chosen as they gave the best approximation to the low strain rate tension and compression test data. In order to account for strain rate dependency and energy loss, the coefficients of both material models had to be adjusted and an artificial Beta damping factor included. The core 'tuning' process was then used to refine the cloth layer and validate the complete ball model. However, the use of artificial damping in both the core and cloth models increased computation time and reduced the stable time increment. An automatic time incrementation scheme based on the highest element frequency in the whole model gave a smaller stable time increment than the true stability limit. This resulted in a minimum time increment of 1.65E-8 for the most critical elements and an overall stable time increment of 2.12E-8 for all other elements.

Impacts of complete balls at speeds ranging from 15 m/s to 50 m/s were recorded with a HSV camera at a rate of 10000 frames per second. COR, impact time and maximum horizontal and vertical ball deformation values were measured and compared with the model data, as shown in figures 12 to 15. The same trends as the core results are observed for those of the complete balls. Two different impact locations were chosen for the model data to assess the effect of cloth anisotropy on ball deformation, and it can be seen that impact location does not have a significant effect on COR. However, impact time and deformation values are slightly affected by the impact location which could indicate that anisotropy of the tensile layer affects ball deformation.

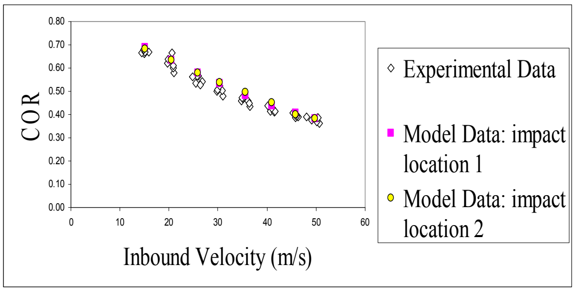


**Figure 12.** COR values for ball model and experimental data.

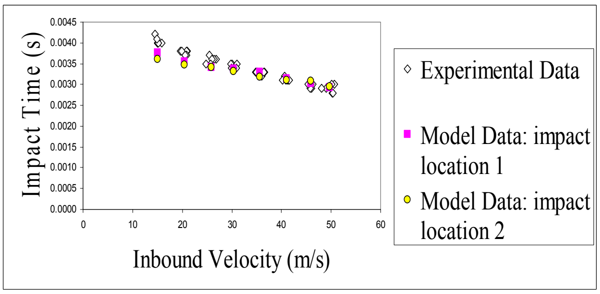


**Figure 13.** Impact time values for ball model and experimental data.

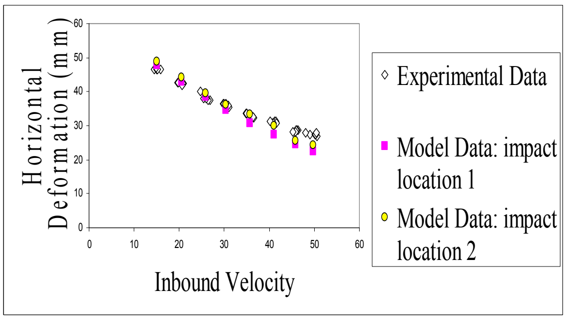


**Figure 14.** Horizontal deformation values for ball model and experimental data.

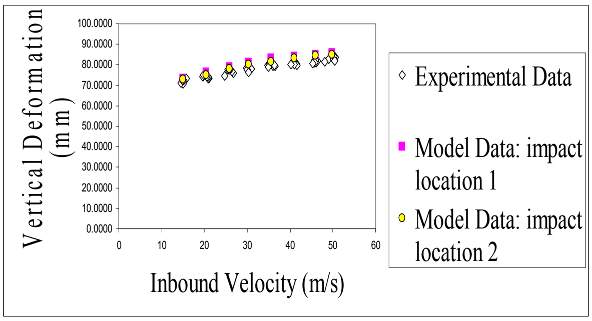


**Figure 15.** Vertical deformation values for ball model and experimental data.

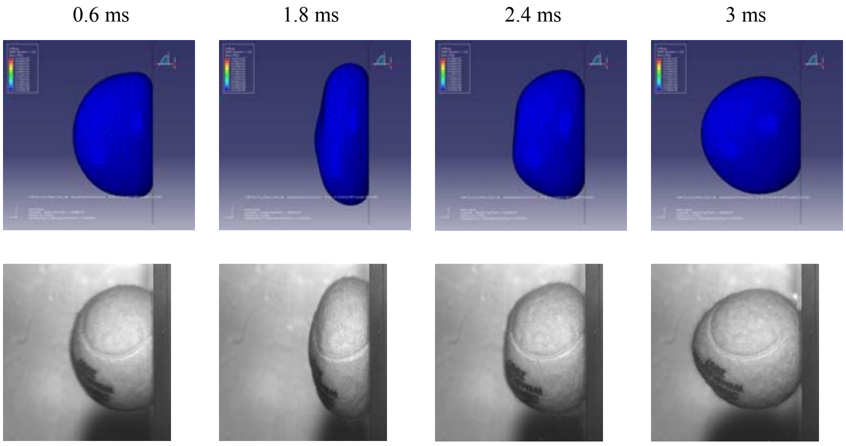


**Figure 16.** Time sequenced analysis of ball motion for an impact at 30 m/s with the model at the top and the experiment at the bottom.

Figures 12 to 15 show that the model data is in good agreement with the experimental results with a maximum of 7% error for velocities up to 35 m/s and about 10% error for velocities up to 50 m/s for all parameters. The validity of the model was also confirmed by a time sequenced analysis of ball motion throughout the impact, shown in figure 16. The shape of the ball in the simulation (at the top) closely matches the one from the experiment (at the bottom). Figure 16 also shows that the ball deforms slightly asymmetrically during impact, which is a consequence of the anisotropic properties of the cloth and might affect rebound consistency. When comparing the core and complete ball parameters, it appears that the addition of the cloth has the effect of stiffening the composite ball as its deformation is reduced. However, the complete balls have longer impact time and lower COR values, indicating that a significant amount of energy loss is due to the cloth layer.

## 4. Conclusions

The viscoelastic properties of the core and the fabric of a pressurised tennis ball have been successfully modelled using a 'tuning' process to account for strain rate dependency together with the addition of an artificial damping to account for energy losses. This method has enabled normal tennis ball impacts to be accurately simulated at velocities encountered in professional tennis. An increase in the inbound velocity resulted in a decrease in COR, impact time and horizontal deformation and an increase in vertical deformation for both cores and cloth covered balls. Material tests showed that cloth anisotropy should not be neglected when developing a tennis ball FE model as it appears to affect ball deformation. Further work is required to extend the model's capability for other game impact scenarios.

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