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Procedia Structural Integrity 8 (2018) 345–353

Structural Integrity Procedia

www.elsevier.com/locate/procedia

AIAS 2017 International Conference on Stress Analysis, AIAS 2017, 6-9 September 2017, Pisa, Italy

A study on the dynamic structural behavior of Olympic sabres

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Abstract

Sabres used in Olympic fencing are subject to severe elastic deformations during matches and training sessions. Even though strict rules for their manufacturing are prescribed by the international fencing federation, with requirements in terms of geometrical constraints and material (steel) properties, nonetheless frequent unexpected ruptures are observed. These may cause injuries to the fencers, and involve the replacement of the blade. In this study an experimental-numerical approach is adopted to investigate the underlying failure mechanisms. To this purpose, several attacks, “bouts” in fencing, were live filmed during actual practice with digital cameras and a trajectory tracking analysis was performed on the most critical of them, taking advantage of markers fixed on the blades at different positions. The post-processed data were subsequently used as boundary conditions of a 3D finite element model of the blade. Running a non-linear transient analysis, global and local quantities such as maximum stored elastic energy, stress and strain states, strain rates and possible permanent plastic strains were evaluated. A validation of the FE model with experiments was also carried out. From the critical analysis of experimental and numerical results it was possible to speculate about the influence of materials and dynamic related effects on the structural behavior of the blade. Eventually, hypotheses on fracture mechanisms were formulated.

Peer-review under responsibility of the Scientific Committee of AIAS 2017 International Conference on Stress Analysis

Keywords: *Olympic sabres; Trajectory tracking; FE Analysis; Damage assessment;*

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Peer-review under responsibility of the Scientific Committee of AIAS 2017 International Conference on Stress Analysis
10.1016/j.prostr.2017.12.035

1. Introduction

Sabre is an Olympic sport since 1896, the equipment showing many peculiar engineering features during operation (blades are subject to very large elastic deformations and possibly plastic deformations). As a matter of fact, frequent unexpected ruptures are observed during trainings and matches, despite stringent specifications in terms of geometry and materials imposed by the International Association of Athletics Federations (IAAF Rules for Competition, 2016). Some of these ruptures may create sharp corners potentially dangerous for the athletes. Furthermore, these failures contribute to shorten the average sabre life (i.e. around two weeks) increasing the expenses for practicing the activity, since the cost for a good quality unit is quite high. It is worth noting how very few investigations on this topic are available in the literature, Chen et Al (2017). It has been observed in Coppola et Al (2016), that the sabre fracture behavior depends from a number of factors not fully quantified yet, and not directly related to the fracture type. Among them we can indicate the blade geometry and steel microstructure, mass, speed and fencing style of the athletes.

The present paper focuses on the analysis of the most critical kind of bouts, which has been identified partly relying on a previous study from Coppola et Al (2016), and partly on field observations during training with athletes performing actual bouts. The most severe condition for the sabres occurs when both athletes go in lunge at the same time: in this case the inertia of the two bodies moving one towards the other contributes to produce severe loads on the blades. Based on this challenging condition, an experimental-numerical dynamic study was performed to quantify the absorbed elastic and plastic energy, the state of stress and strain at critical points, and plastic deformations, if present. All results will be presented and discussed in the paper. The increased know-how on the mechanical behavior of the sabre will be useful to understand underlying failure mechanisms, improve the performance of such sporting tools, in terms of resistance, duration and safety, and might also lead to the identification of an equivalent laboratory test to be used as a certification for these sporting tools.

2. Experimental activities

The experimental activities were devised to measure the position and velocity of different points of the sabre during an actual bout. To this purpose many lunges were live filmed in a gym by using a digital camera to be successively post processed through a dedicated 2D analysis software. The acquired data will provide information on the structural dynamic behavior of the equipment and will serve as boundary conditions for a numerical structural simulation of the bout as well as for its validation. Capabilities and limits of single camera tracking in biomechanics are well documented in the literature, see for instance Pentenrieder et Al. (2006) and Yang et Al (2013).

A black uniform background was chosen for the scene, to maximize the contrast with performers, while two light sources were arranged to prevent cast shadows. The blades of the sabres were treated with an anti-reflective coating to limit reflection. In addition, several yellow and red markers were placed on the blade to be recognized by the video analysis software. They were spaced with an increasing density towards the tip, being the sabre stiffness non uniform because of its tapered geometry, which induces the largest deformations close to the tip itself. It is worth noting that failures are usually observed in this region of the blade. The camera distance from the athletes was chosen to frame the whole sabre shape during lunge movements and to have the action, and hence the contact between the athletes and the sabres, centered in the image. Several shooting session were performed, and the most significant lunges were successively identified. The performers, professional athletes, were asked to execute lunges as much as possible on a plane of motion perpendicular to the axis of the camera, to reduce perspective distortions. Each video was recorded at 240 fps with a consumer type digital camera.

The most severe lunges, presenting a residual plastic deformation on the blade, were analyzed with the free software Tracker (http://physlets.org/tracker). It offers a smart auto-tracking function, which seeks a target pattern of pixels defined in the first frame within a region of interest, in the subsequent frames, using digital correlation functions. After imposing the global coordinate system and scaling factors, positions and velocities of the markers over time could be obtained using the auto-tracker. The final result is visible in Fig. 1, showing some snapshots of the most critical lunge analyzed, that will be presented in this work (on the left), along with the deformation of the blade over time (on the right), relative to the handle.

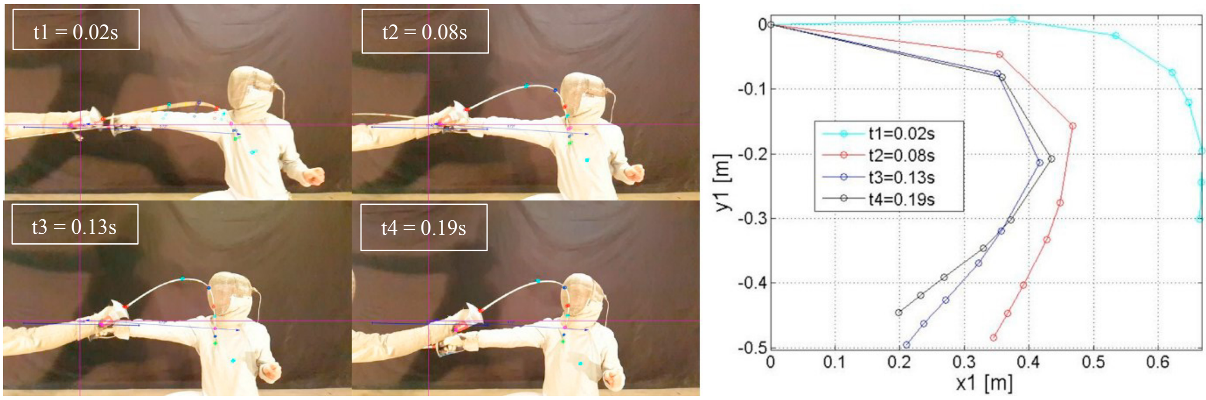

Figure 1: Selected critical bout. Snapshots taken at different instants and corresponding post processed blade deformation.

To obtain the data of Fig. 1, many post-processing operations were carried out, to correct projection errors associated with 2D images acquisition. As hypothesis, a planar deformation of the sabre was assumed, provided that its cross-sections are Y shaped, thus presenting one of the principal moments of inertia much higher than the other. Nevertheless, the position of the deformation plane during a bout is unknown, and it does not necessarily coincide with the plane of the images. The misalignment can be caused both by the rotation of the arm and of the wrist of the athlete during lunges. For a correct tracking, the marker coordinates must be projected back on the deformation plane from the plane of the image to be representative of the actual positions assumed by the points of the blade. Two parameters are needed to describe the position of the deformation plane x_1-y_1 with respect to the image plane x-y: α indicates its rotation along the vertical axis y (corresponding to an out-of-plane movement of the arm), while θ describes its inclination with respect to the x axis (due to the rotation of the wrist), see Fig. 2. The analytical relations describing the transformation of coordinates are reported in (1).

$$\begin{cases} x = x_1 \cos \alpha \\ y = y_1 \cos \vartheta \end{cases} \tag{1}$$

The length of the blade can be regarded as constant, given that its axial deformation is negligible compared to the flexural one. This assumption was exploited to find α and θ, matching the nominal length of the sabre with the measured length, calculated from the corrected positions of the markers. From experimental observations, α seemed to remain constant after the contact of the sabre tip with the athlete, such that it can be identified from the first acquired frames before contact and kept unchanged afterwards. This means that only θ had to be recalculated frame by frame for the whole duration of the lunge.

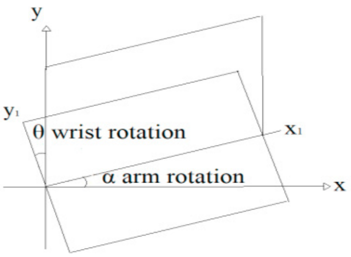

Figure 2: Position in space of the deformation plane x_1-y_1 with respect to the plane of the acquired images x-y.

An optimization procedure was set-up to retrieve the optimal position of the plane. Preliminarily, a trial deformation plane was chosen, the coordinates of the markers were projected on it from the image plane, and an Hermite interpolation was adopted to calculate the actual length of the sabre. Then, an error function, namely the difference between the nominal (880 mm) and the measured length, was minimized in two subsequent steps to find α and θ. In the first step α was calculated using all frames before contact. The value assumed by θ had no influence here, under the hypothesis of an undeformed sabre before contact. A best fit value of 29.8° was found for the bout of Fig. 1. In the second step the best values θ were calculated, for each frame, keeping the previously evaluated α value constant: an initial value at the onset of contact was 41.3°, and the range during contact was 40°-50°. Thanks to this procedure the kinematics of the marked points of the sabre during the whole duration of the critical bout could be reconstructed.

3. Numerical analysis

Within geometrical limits imposed by international rules to the sabre blade geometry, different shapes are nevertheless possible; therefore, it was necessary to retrieve the exact dimensions of the equipment used in the experiments. This task was accomplished by measuring the dimensions of several cross-sections along the blade itself, using a manual caliper first, and a structured-light scanner Atos Core 300 from GOM Gmbh afterwards, to be able to measure the small geometrical details and curvatures of the sections. Using these data, a 3D solid model was created using a CAD software. The model was subsequently imported in the Finite Element code Ansys, to perform a structural analysis reproducing the lunge.

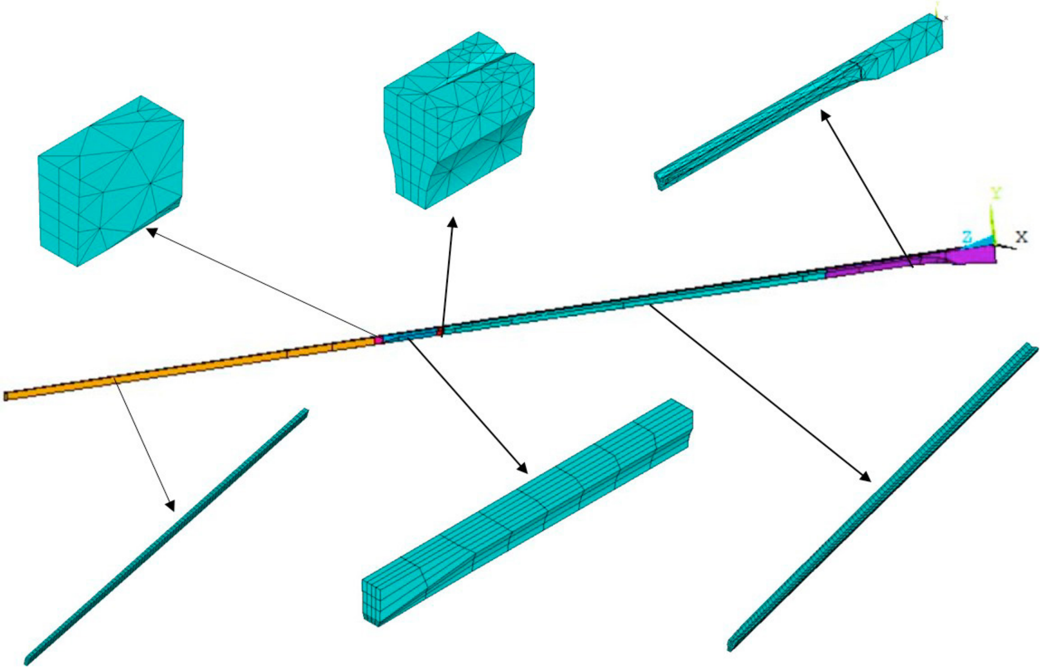

Figure 3: 3D finite element model of the blade, with details of the mesh strategy and density.

In the numerical model, see Fig. 3, a bilinear elasto-plastic rate independent constitutive material model was used, with a Young modulus of E=210 GPa, Poisson ratio ν=0.3, yield stress σ_s=1.9 GPa and a work hardening tangent modulus Mt=2.24 GPa. These values, taken from the literature, are compliant with the minimum requirements imposed by the International Association of Athletics Federations (IAAF Rules for Competition, 2016), corresponding to the typical characteristics of a maraging steel. The discretization of the solid model was designed to reduce as much as possible the distortion of the mesh; due to its complex geometry the volume was divided into six simpler parts, which were meshed using both free quadratic tetrahedral elements (Solid 185) and structured brick (Solid 187) elements, counting a total of about 23000 nodes for the whole model. Large displacements and all non-linear features of FE code were activated to account for the high elastic and plastic deformations involved in the analysis. Boundary conditions were referred to a local coordinate system with the origin on the handle, with the x axis aligned with the axis of the sabre, and the y axis such as the x-y plane coincided with the deformation plane. Experimentally measured displacements were recalculated with respect to this relative system. The blade end at the handle side was fixed, while, to reproduce the experiments, the displacements of two points were imposed as boundary conditions in the numerical model. These two points corresponded to the contact points at the tip and at an intermediate point of the blade with the body and the helmet of the athlete, respectively (see again Fig. 1). Due to the geometrical and material non-linearities, the boundary conditions were applied in small sub-steps within a transient analysis; auto time-stepping capabilities of the code were used to facilitate convergence. Fig. 4 shows the output of the simulated bout, in terms of contour maps of total displacement.

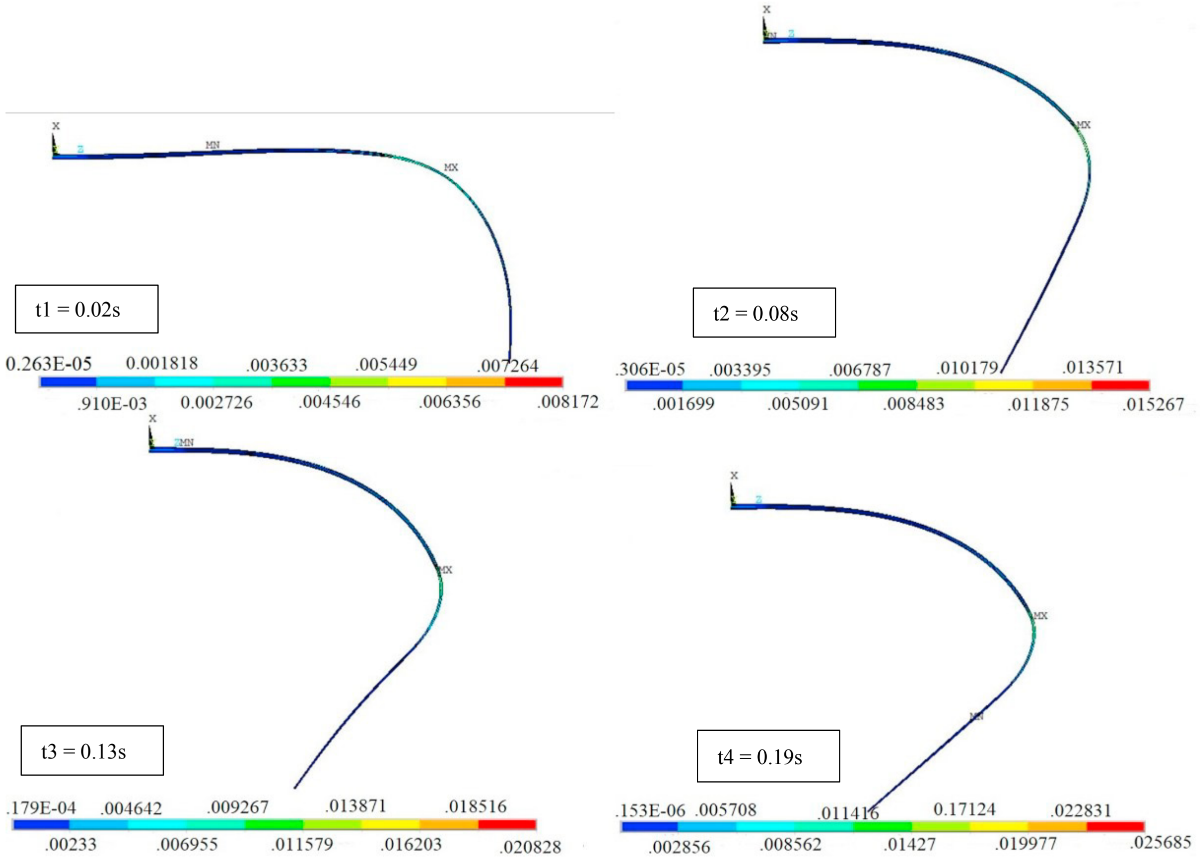

Figure 4: FE model, deformed shape (in meters) during four successive instants (t = 0.02 s, 0.08 s, 0.13 s, 0.19 s) of the bout.

The accuracy of the numerical model was proved comparing, over time, the tracked and simulated positions of selected markers. Firstly the differences during the evolution of the bout were checked. Tab. 1 illustrates the results obtained: maximum measured displacements of the markers are reported, along with the differences with respect to the corresponding numerical values.

Table 1: Experimental-numerical comparison during the bout.

Marker distance from handle	540 mm		710 mm		790 mm		840 mm	
Displacement component	Uy_1	Ux_1	Uy_1	Ux_1	Uy_1	Ux_1	Uy_1	Ux_1
Experimental max displacement	183 mm	85 mm	322 mm	345 mm	377 mm	482 mm	394 mm	566 mm
Difference with simulation	8%	11%	3%	0%	4%	1%	0%	1%

Afterwards the residual displacements of the plastically deformed blade after the elastic recovery (springback) were compared, see Tab.2. Fig. 5 presents an additional visual comparison between the sabre after the bout and the corresponding FE simulation, showing a contour map of the residual total equivalent plastic deformation, and a detail of the most deformed part of the numerical model.

The match for the loading phase vas very good, while larger errors were found for the second checked configuration. This can be attributed to the inaccuracy of the numerical simulation in capturing the springback effect. This issue is known and documented in the literature, for instance in Ghaei (2012) and Broggiato et Al. (2012).

Table 2: Experimental-numerical comparison after the bout.

Marker distance from handle	540 mm		710 mm		790 mm		840 mm	
Displacement Component	Uy_1	Ux_1	Uy_1	Ux_1	Uy_1	Ux_1	Uy_1	Ux_1
Residual displacement	9 mm	1 mm	36 mm	4 mm	55 mm	7 mm	63 mm	8 mm
Difference with simulation	0 %	1 %	42 %	37 %	58 %	33 %	61 %	39 %

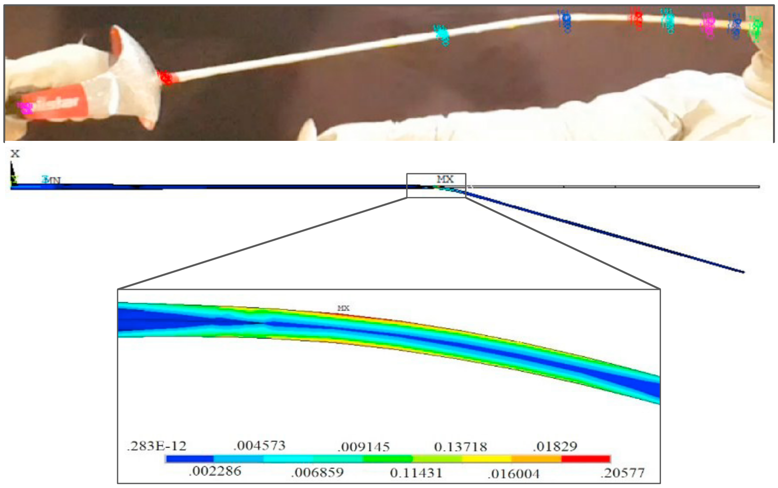

Figure 5: FE model, deformed shape at the end of the bout, experimental-numerical comparison and details of the plastically deformed area in the numerical model.

To sum up, the numerical model was regarded capable to reproduce the real behavior of the sabre during bouts with a reasonable approximation, and can therefore be used to speculate about the inner local structural stress and strain state of the equipment.

4. Results and discussion

Some considerations about the dynamic behavior of the sabre can be formulated thanks to experiments and relying on the previously validated numerical model. As first, the impact velocity and the mean strain rate in the material were calculated, to verify if dynamic effects arise, related both to inertial masses, and to the response of the material. Impact velocities, obtained from the video post-processing, were in the range from 15 to 20 km/h. The mean strain rate was calculated as the ratio of the maximum plastic deformation to the time difference between the first step in which it manifested and the step corresponding to its maximum: the value was 0.118 s^{-1}. These results suggest that dynamics has a marginal influence: impact velocity is too limited for inertial effect to be significant and strain rate is low when compared to the typical values which can modify the material constitutive behavior for steels. As a consequence, simpler quasi-static experiments and static simulations can be used without compromising accuracy. This is a clear advantage, for instance, in a possible design of a laboratory test bench for the qualification of the sabres. In this context, the total deformation energy was also estimated from FE analysis, calculating the external work done on the blade from the knowledge of loads and displacements during the bout. Fig. 6 summarizes the evolution of the stored total energy over time; a maximum value of 113 J was observed. This number could be useful to develop a laboratory test at an equivalent energy level.

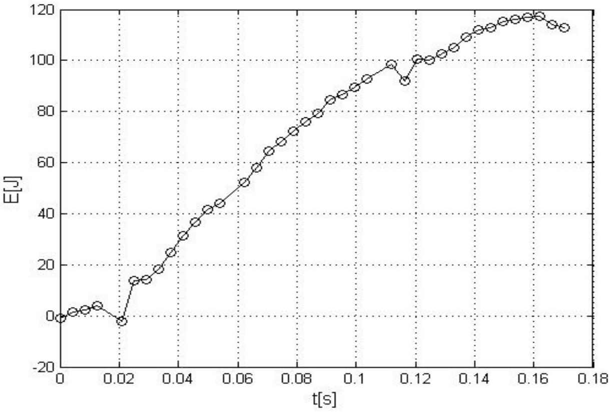

Figure 6: FE model: evolution of total energy accumulated during the bout.

Moreover, some speculations about possible failure modes could be put forth. The FE analysis showed that the maximum equivalent Von Mises stress, in the most critical section, was about 2190 MPa, with an associated equivalent plastic deformation of 0.017 mm/mm. Also, the experience collected from trainers and athletes reports that after a severe bout with permanent deformation of the blade, this is manually straightened, applying a reverse plastic straining. These facts suggest that failures might be caused by cumulative damage related to low-cycle fatigue, leading to a final ductile rupture. Metallographic analyses would be useful to confirm these hypotheses and quantify the modifications in the microstructure. Also, simulations including ductile damage models and material degradation could be performed to prove the consistency of the assumptions, see Bai and Wierzbicki (2010), Cortese et Al. (2016a), Cortese et Al. (2016b).

Beside the considerations on failure modes, a parametric study on the effect of the material properties was performed. Namely, Young modulus and Poisson coefficient were kept fixed, provided their limited variability with alloy content in steels, while the yield stress (σ_S) and the tangent modulus (Mt) of the bilinear constitutive model were varied one at a time in a reasonable range of possible candidate materials, discretely. FE simulations were run accordingly, and the effect of the parameters was investigated in terms of variations of total energy absorbed during the bout and residual displacements at the end of the attack. The results of this sensitivity analysis are reported in Fig.7. It can be observed how more performant materials, with increased yield limits and higher work hardening could lead to a reduction of residual plastic displacement which is an advantage, with only a limited increment of energy absorbed by the equipment due to the larger amount of elastic energy stored as a downside.

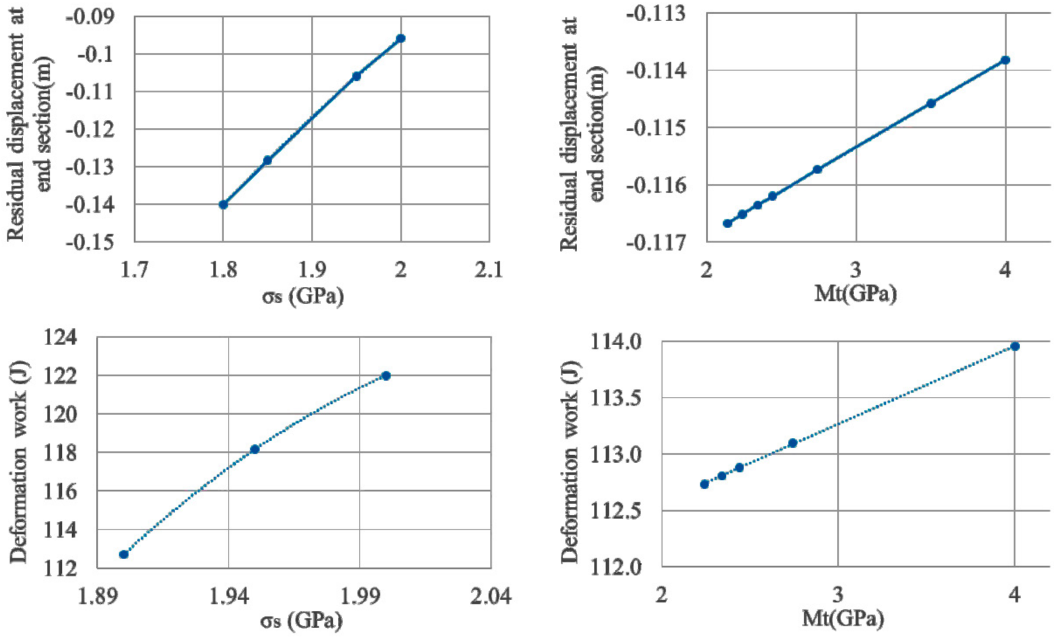

Figure 7: Effects of material properties variation on the sabre structural behavior during an actual bout.

5. Conclusion

An experimental-numerical approach, 2D video analysis coupled with a FE analysis, was employed to study the static structural and dynamic behavior of Olympic sabres. This innovative method proved to be valuable, allowing to evaluate several different quantities (i.e. impact velocity, mean strain rate, critical stress states, plastic deformations and deformation energy), which have influence on the sabre mechanical behavior. The impact velocity and strain rate seemed to have a marginal influence on sabre response, while the deformation energy and the residual plastic deformation were identified as possible causes of failure: even though it has to be confirmed by future metallographic analyses, one of the sabre failure mechanism is supposed to be associated to low-cycle fatigue damage accumulation.

Acknowledgments

The authors wish to thanks SS Lazio Scherma Ariccia, and in particular the trainer responsible Vincenzo Castrucci, for the cooperation in this study making available a fencing room, and all the athletes who participated in the severe experimental filming sessions.

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