Merits of Employing Carbon Foam Fabrics in Firefighter's Helmet Shell

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Background

- The firefighters rely on their helmets to protect them against both:

1- Mechanical impact stresses caused by falling debris.

2-Thermal Heat stresses caused by fires .

…….*Background*

A proposed firefighter's helmet **MUST** pass two tests:

1- Impact test

2- Flame test

- ***Generally*** a firefighter helmet consists of two important layers namely: the helmet shell and the impact liner.

…………Background

In general the helmet should possess the following characteristics:

- Impact resistance
- Thermal resistance
- Light weight
- Durability

Carbon Foams

Carbon foams are cellular materials that have been considered recently in variety of applications due to their:

1- Extremely light weight.

2- Optimum mechanical and thermal properties.

3- Ability to be used as thermal insulators.

4- Due to its porosity, it performs very well as a shock absorber.

5- Ability to be used in biological applications.

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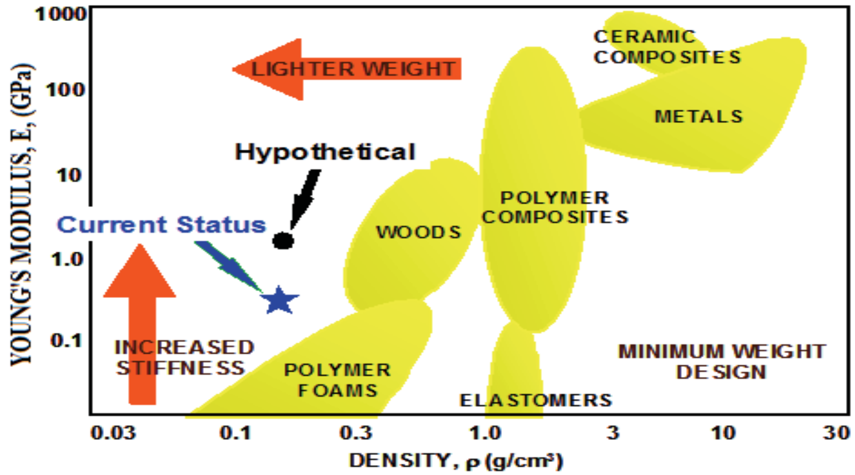

Fig.1 Estimated specific modulus of pitch-based carbon foam and other competing materials

Fig.2 Fig.1 Carbon foam as an insulator

Objectives

The present work is numerical and experimental studies to investigate and predict the merits of using carbon foam fabric as an alternative material for firefighter's helmet.

1- Numerical Approaches

Several types of carbon foams with different :

- Porosity
- Density
- Thickness
- Thermal conductivity.

Are introduced for the sake of a parametric study.

Test Criteria

1- Impact Test

According to NFPA 1971 Test Methods; the mechanical strength of helmets is tested by an Impact test where a hemispherical impacter is dropped on the helmet-headform set-up and the force transmitted on to the headform through the helmet has to be less than 3780 N.

Model Description

- A 3D simulation is used to model the carbon foam helmet shell, carbon foam impact liner, a hemispherical striker and a headform.

- For testing the mechanical strength of carbon foam, simulations of impact tests are conducted using Abaqus CAE dynamic explicit solver in which a hemispherical striker is made to fall freely on the helmet firmly seated on a headform.

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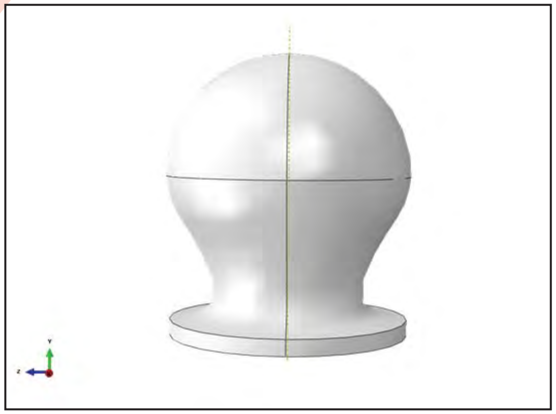

Fig.3The geometric model of the Al headform generated in ABAQUS

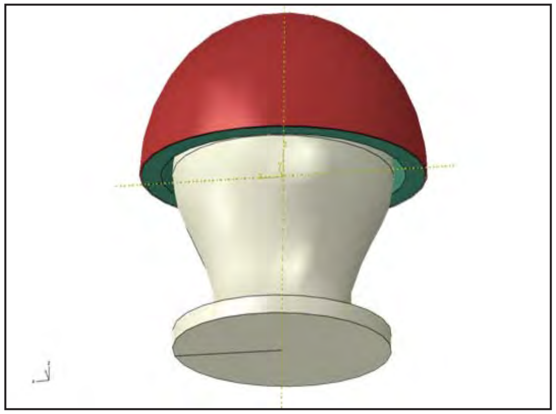

Fig.4The assembled geometric model of the helmet shell,(in red) impact liner , (in green) ,and headform , (in white).

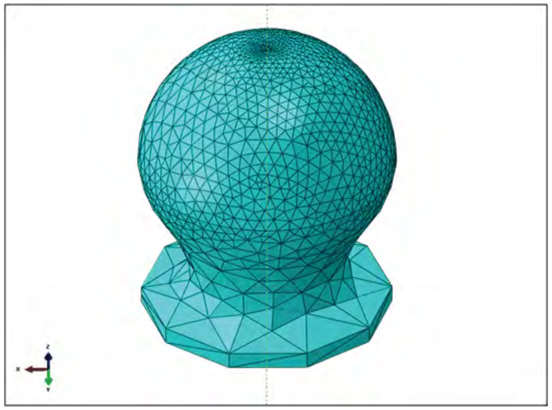

Fig.5The meshed geometric model of the headform

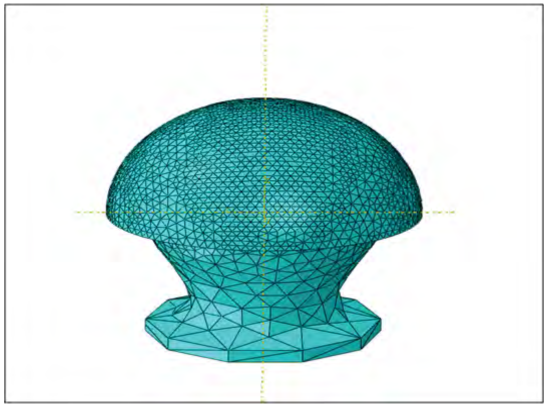

Fig.6The meshed geometric model of the helmet seated on the headform

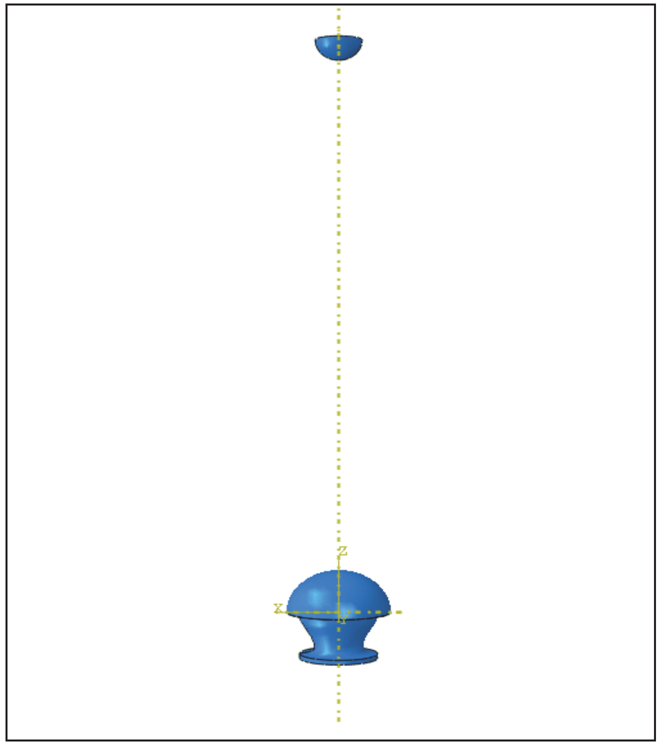

Fig.7The assembled geometric model of the impact test setup

Model Validation

- We have verified the Crushable foam model employed by the Abaqus CAE software by conducting a three dimensional dynamic simulation of the low-velocity impact experiment and validating its results with the experimental results of Rizov[16].

- Figure 8 shows a good match between the two results.

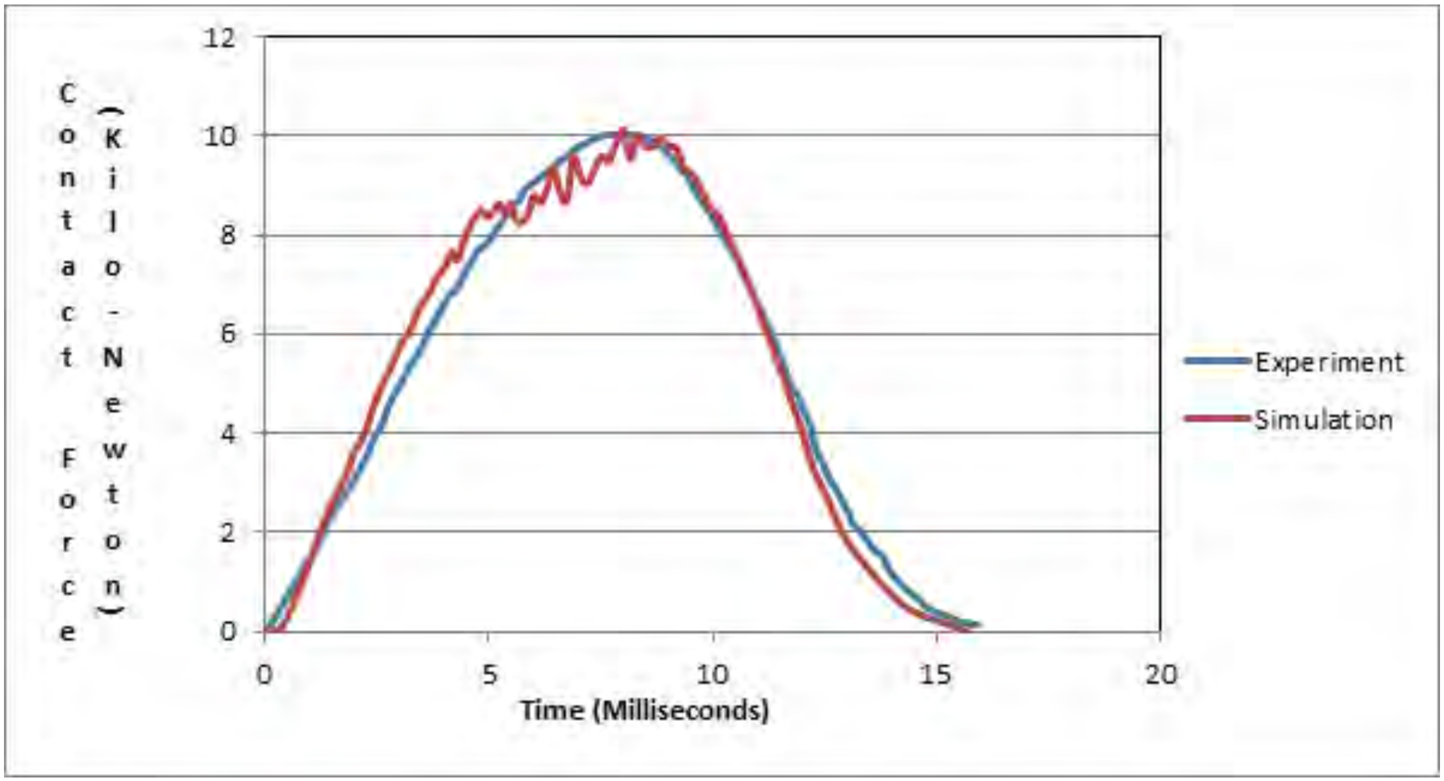

Fig. 8 Validation of present simulation model with experimental results, Rizof [16]

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Carbon Foam with	Density (kg/m^3) of the foam with solid ligament density of 1400 kg/m^3	Density (kg/m^3) of the foam with solid ligament density of 1200 kg/m^3	Young's modulus (MPa)	Poisson's ratio	Yield strength (MPa)
0.05 porosity	1330	1140	76.71×10^3	0.33	187.96
0.10 porosity	1260	1080	68.85×10^3	0.33	173.35

Table.1 Material Properties of Carbon foam used in helmet shell

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Carbon Foam with	Density (kg/m^3) of the foam with solid ligament density of 1400 kg/m^3	Density (kg/m^3) of the foam with solid ligament density of 1200 kg/m^3	Young's modulus (MPa)	Poisson's ratio	Yield strength (MPa)
0.95 porosity	70	60	62.5	0.33	2.85

Table.2 Material Properties of Carbon foam used in impact liner

Results

1- Effect of Porosity

The first simulation; case-1 has been carried out by using carbon foam with 0.10 porosity and 1260 kg/m^3 density in the helmet shell and carbon foam with 0.95 porosity and 70 density in the impact liner. The helmet firmly seated on the headform is impacted by freely falling hemispherical striker weighing 3.53 kg from a height of 1.53m. The net thickness of the helmet is 0.0165m (helmet shell being 0.0015 m thick and the impact liner 0.015 m thick), Fig. 9.

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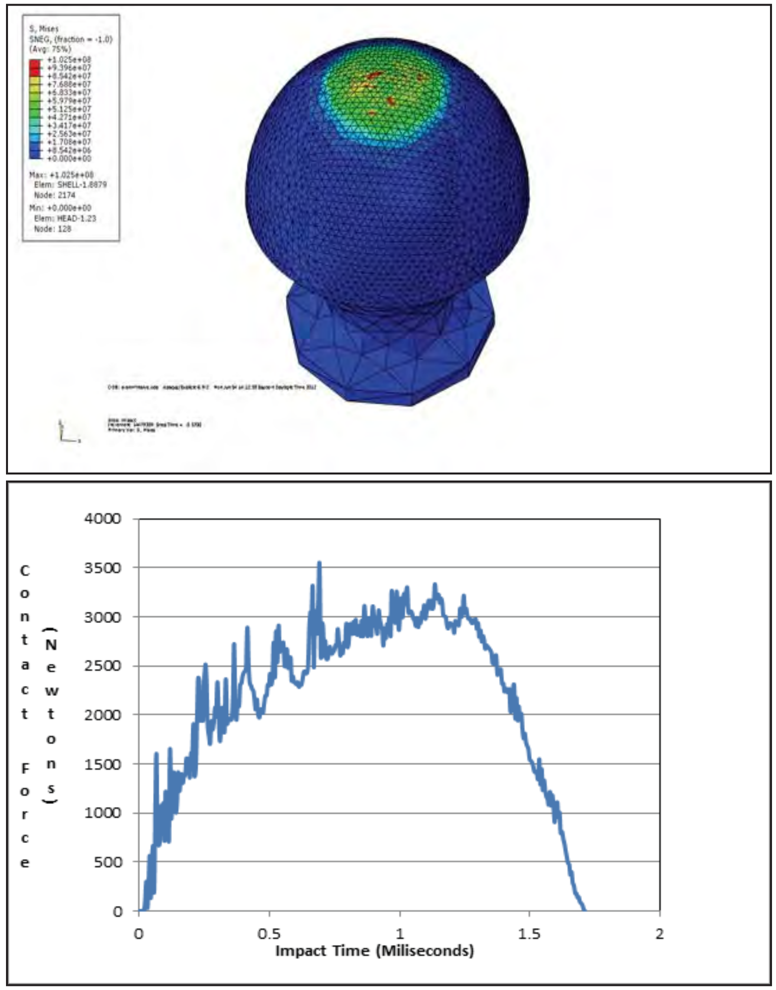

Fig. 9 Stress contours & Contact force on the headform during the impact test, case-1

- Figure 9 shows that the peak force measured on the headform was 3534.12 N which is below the NFPA standard of 3780 N. Also, the maximum Mises stress on the helmet shell is found to be 1.025 × (10)^8 Pa which is less than the yield strength 1.8796 × (10)^8 Pa of the carbon foam in the helmet shell.

- With the parameters used in case-1, the net weight of the helmet will be **0.2702** kg compared to **0.6928** kg if regular materials are used. Thus, the carbon foam helmet designed in present study is **60.99 % lighter** in weight than a regular firefighter helmet.

2- Effect of density

In case-2 carbon foam with 0.10 porosity in the helmet shell. While the overall density of the carbon foam is1080 kg/m^3. For the impact liner, carbon foam with 0.95 porosity and of 60 kg/m^3 is used, Fig. 10.

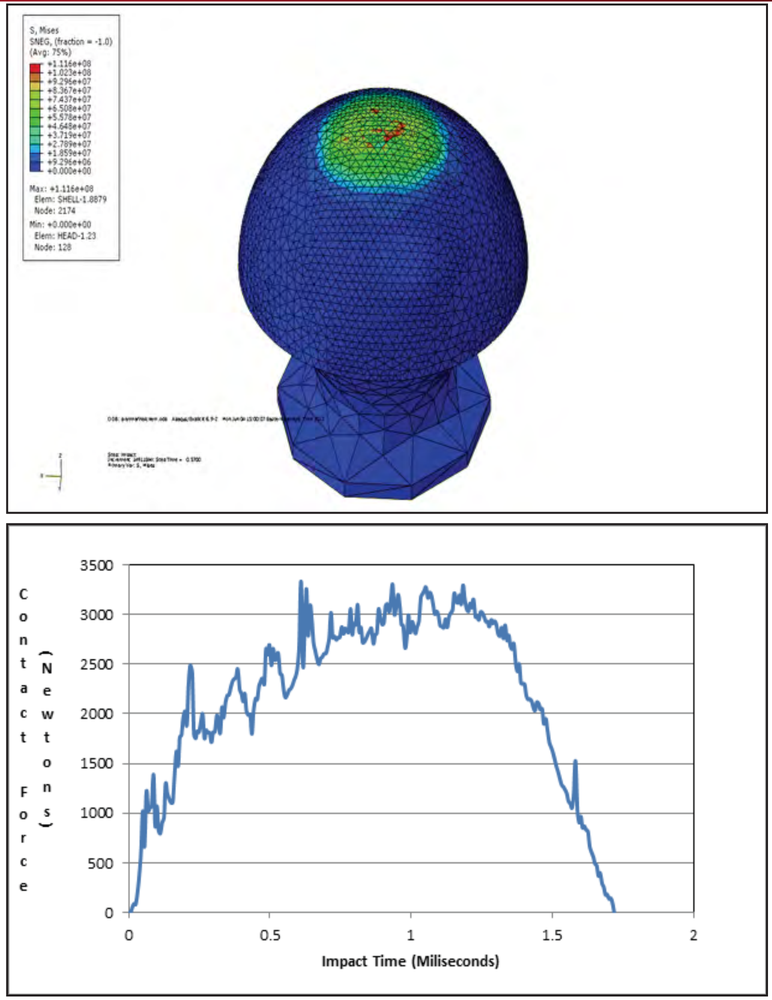

Fig. 10 Stress contours & Contact force on the headform during the impact test, case-2

By comparing the results of case-1 and case-2 a considerable decrease in the peak force is noticed. On the other hand, the peak stress value on the helmet shell increases in case-2 when compared to case-1. Also with the decrease in density of the carbon foam in the helmet, the net weight of the helmet was **0.2318** kg in case-2, which is **66.54%** less than a regular firefighter helmet weight.

3- Effect of Thickness

In case-3 the helmet thickness is 0.0165m. The same parameters for case-1 were used.

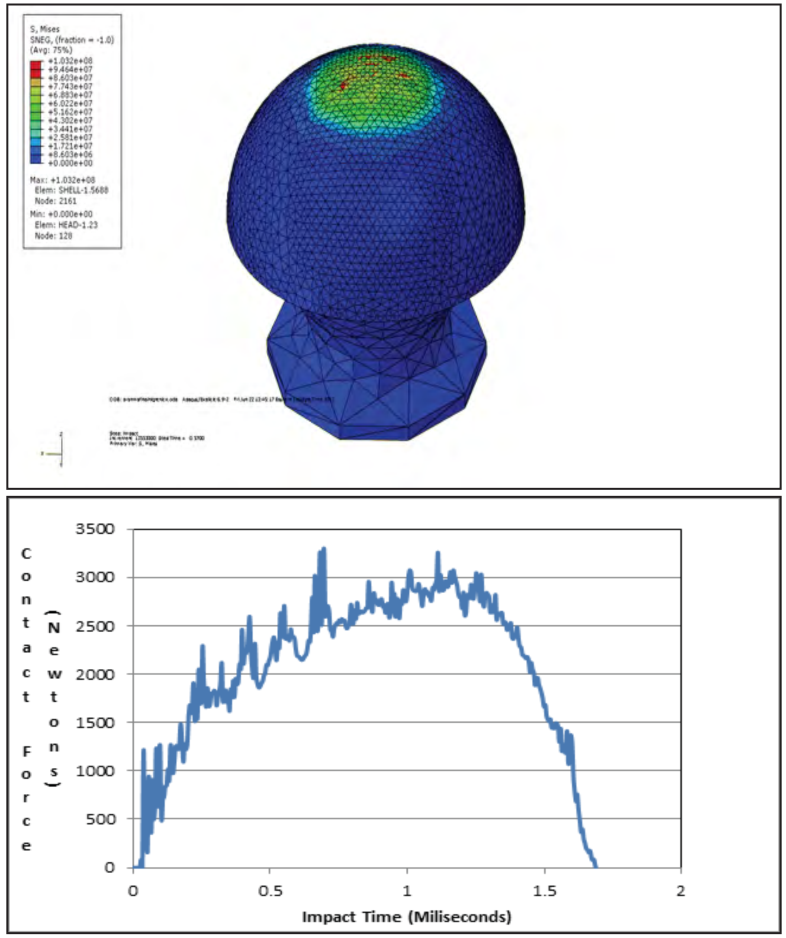

Fig. 11 Stress contours & Contact force on the headform during the impact test, case-3

-Figure 11 shows that in case-3; the peak force measured on the headform is 3262.36 N which goes even more below the NFPA standard of 3780 N. Also, the maximum Mises stress on the helmet shell is still found to be 1.032 x (10)^8 Pa which is less than the yield strength 1.7335 x (10)^8 Pa.

-The net weight of the helmet is 0.2992 kg in case-3, which is 56.81% less than a regular firefighter helmet weight

Test Criteria

2- Flame Test

According to NFPA standards, the flame test is conducted by applying a fire flame to the helmet shell at a temperature of 1200 C for a time period of 15 seconds.

Model Description

- A Simulation incorporating similar conditions is performed in Fluent CFD software. A double precision pressure-based implicit solver, under unsteady/transient state condition has been used.

- The required flame effect is produced by providing heat to the helmet shell in the form of both radiation and convection.

- Present study focuses on monitoring the temperature drop along the thickness of the helmet in a unidirectional approach.

Model Validation

The present thermal simulation model has been applied on a case of study introduced by Song et al. [7] to ensure its validity, Fig.12

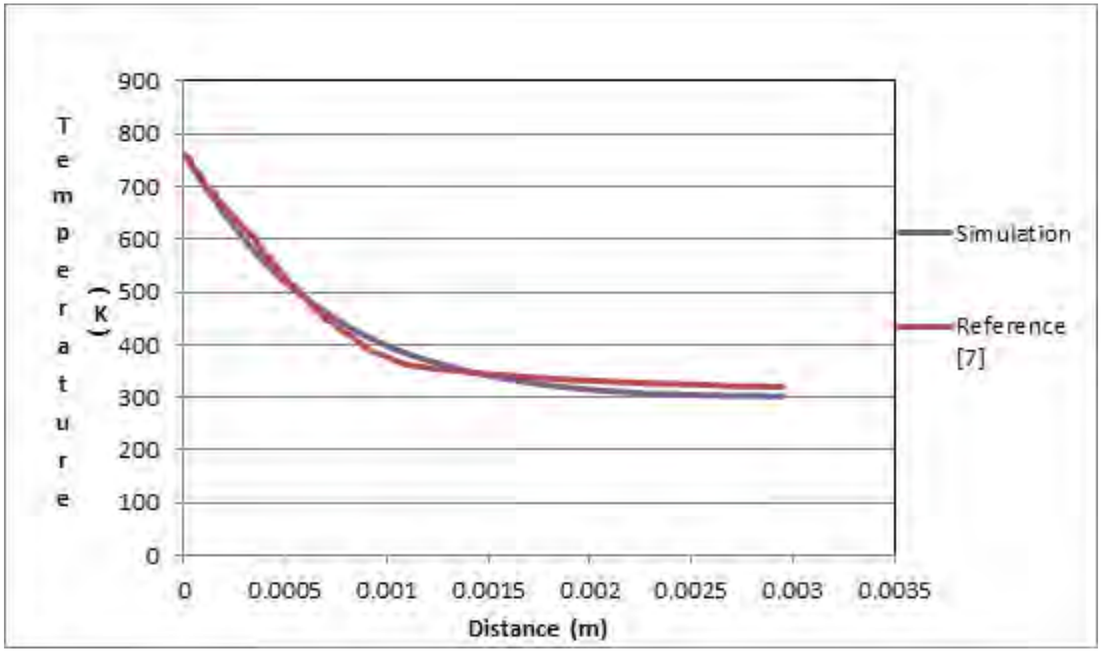

Fig. 12 Validation of present simulation model with ref. [7]

Results

1- Effect of thermal conductivity

In case-4, the net thickness of the helmet is 0.0165m. The porosity of the carbon foam in helmet shell is 0.05 and 0.95 in impact liner. The thermal conductivity of used carbon foam is 0.22 W/m-k. The density of solid ligaments in the foam is 1400 kg/m^3. The helmet shell is exposed to a flame at a temperature of 1200 C (1473 K) for a time period of 15 seconds and the temperature drop along the thickness of the helmet was monitored.

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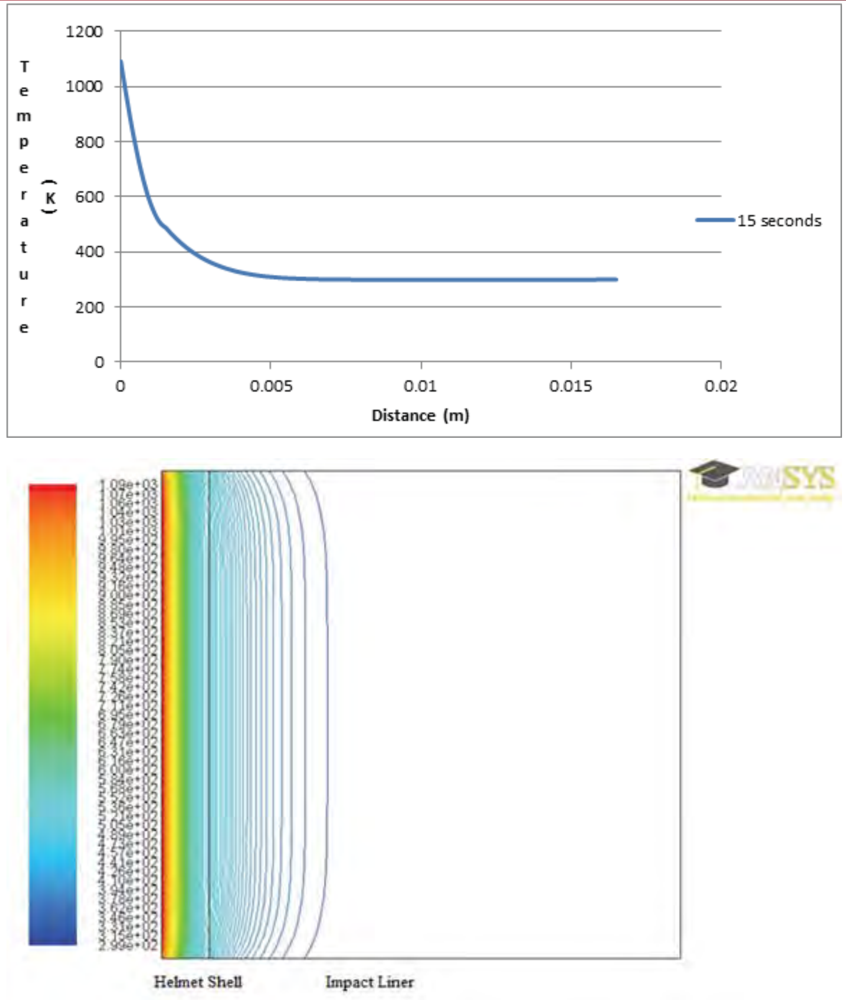

Fig.13 Temperature drop through helmet thickness, case-4

In case-4, the temperature has dropped along the helmet thickness from 1104 K at the outer edge of the helmet shell to 300 K at the inner edge of the impact liner. Figure 13 shows the temperature distribution through the helmet thickness after 15 second exposure to the fire in the form of XY plot and line contours respectively.

2- Effect of porosity

Case-5 has been carried out for the helmet with 0.0165m thickness. The porosity of the carbon foam in the 0.0015m thick helmet shell is 0.05 and the porosity of the carbon foam in 0.015m thick impact liner is 0.95.

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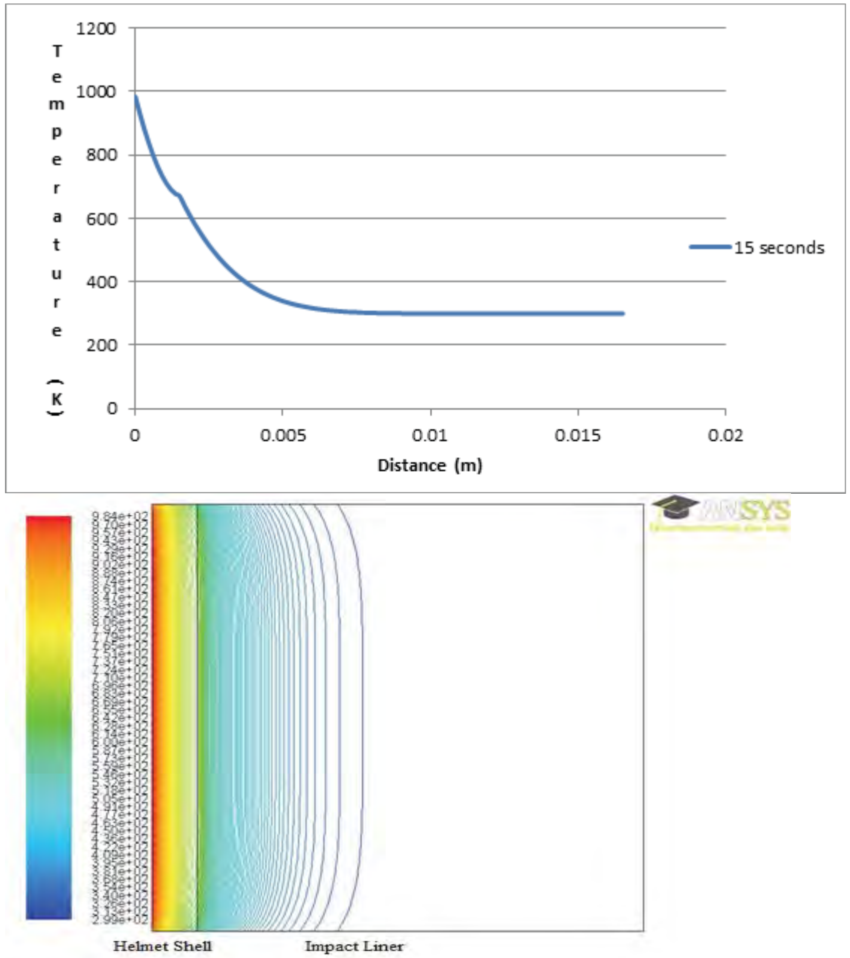

Fig.14 Temperature drop through helmet thickness, case-5

In figure 14, the helmet shell is exposed to a flame at a temperature of 1200 C (1473 K) for a time period of 15 seconds and the temperature drop along the thickness of the helmet was monitored. The temperature has dropped along the helmet thickness at the outer edge of the helmet shell to 300 K at the inner edge of the impact liner

Experimental Method

- The purpose of this test was to monitor the nature of the force transmitted on to the load cell through the carbon foam sheet during the impact.

- A low-velocity impact test was conducted by freely falling striker from extremely low vertical height on a carbon foam sheet placed on a load cell.

- Experimental Set-up:

- A rectangular (0.223 m x 0.19 m) slab of the carbon foam with a thickness of 0.006 m was used as shown in figure 15.
- The carbon foam sample was impacted by a disc-shaped steel striker (diameter of 0.09 m, thickness of 0.006 m and weight of 0.211 kg), Fig. 14 and Table-3.

Fig.15 Rectangular slab of the carbon foam sample

Property	Value
Nominal Density (kg/m^3)	320
Porosity	0.83
Compressive Young's Modulus (MPa)	620

Table-3 Material properties of Carbon foam

The carbon foam slab is placed on a load cell (MTS 661.21 with a load capacity of 100 KN) which measures the contact force transmitted through the slab during the impact. This data was collected using a computer connected to the load cell. Figure 16 displays the MTS load cell that has been used in the experiment. The drop height of the striker was fixed at 0.047m from the top surface of the carbon foam sample. The test was conducted three times to check the repeatability of the result.

Table-16 MTS 661.21 load cell, Structural System Testing Laboratory of University of Cincinnati

Results

-The data was recorded at a frequency of 2000 Hz. The contact force recorded over the impact time period is plotted as shown in figure 17.

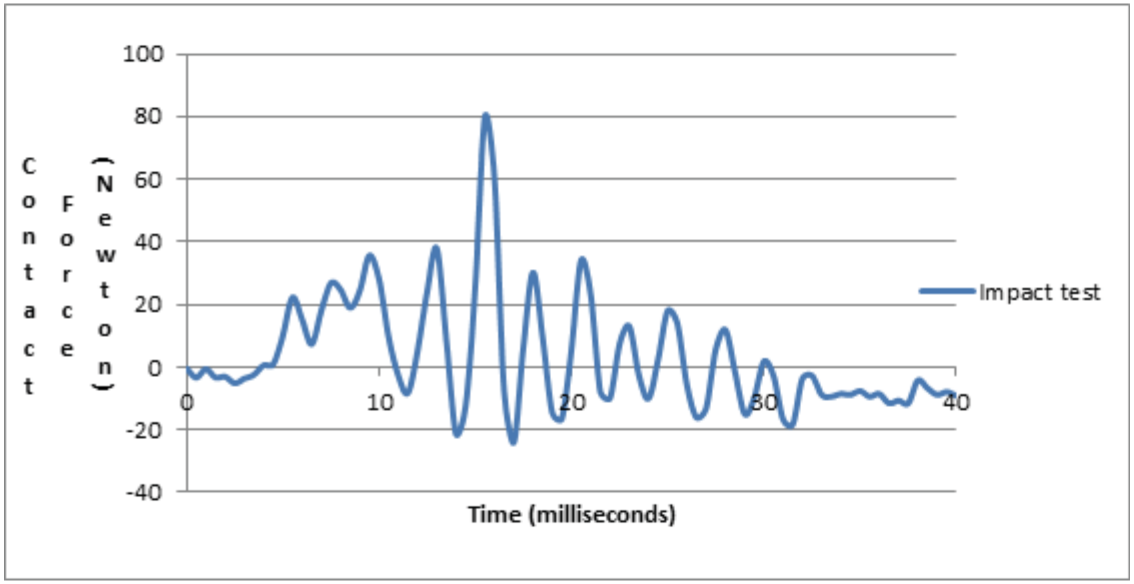

Fig.17 Contact force as measured by the load cell over the impact time period

-The nature of the plot is similar to those obtained in our numerical study of impact test on carbon foam helmet using Abaqus software.

-The constant drop and rise in the contact force is because of the porous and shock absorbing nature of the carbon foams

Conclusions and discussion

-The results of the various simulations of the impact and flame tests show that carbon foam with proposed characteristics is capable in providing both the required mechanical and thermal protection to the firefighter’s head.

-The net weight of the helmet reduces by a percentage range of 57 % to 61 % when compared to the regular materials used in the manufacture of firefighter helmets.

Conclusions and discussion

Carbon foam makes the firefighter's helmet very light in weight increasing the comfort levels for the firefighters along with providing the required protection and durability.

Acknowledgements

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- The experiment was conducted in the Structural System Testing Laboratory of University of Cincinnati under the supervision of Dr. James Swanson.

Thank You

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