ICILSM 2016
22/26 May 2016
Turin, Italy

Crashworthiness modelling of hierarchical short glass fibres reinforced graphene polymer composites materials

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Abstract

This work aims to analyse the response under crashworthiness impact of an automotive crash box composite consisting on short glass fibres that are embedded within graphene reinforced polymer composite. Analytical as well as finite element techniques are employed to derive the overall composite response and mechanical characterisation for a macroscopic structural crashworthiness application. Graphene sheets are considered as platelets GPL embedded within an elasto plastic polymer matrix phase leading to a 2-phases graphene/polymer composite. The modelling of 3-phases short glass fibres/graphene polymer composite consists on a double-scale approach combining the 2-phases graphene polymer composite as matrix phase in which are embedded the glass fibres. The full structure crash box is simulated at each Gauss integration point by implementing the constitutive 3-phases composite using a user-defined materials subroutine.

Keywords: Crashworthiness, Hierarchical modelling, Micromechanics, Graphene composites

Introduction

Lightweighting is a priority for several sectors (e.g. automotive, rail, aerospace) and there is a global drive towards lighter structures for energy efficiency and reduction of carbon footprint. Development of advanced composite materials that offer substantial weight reduction, while improving strength, is in a great demand for the automotive industry. Recently, graphene is at the centre of an ever growing academic and industrial interest because it can produce a dramatic improvement in mechanical properties. Graphene finds direct applications with polymer composite materials where substantial property enhancements have been noticed at much lower volume fraction than polymer composites with conventional micron-scale fillers (such as glass or carbon fibres). Multi scale analyses combining molecular mechanics theories [1, 2] and continuum models have been developed for obtaining the properties of graphene polymer composites. However, there are still much technological challenges to overcome mainly in terms of material modelling. These challenges are characterised by a lack of sufficient knowledge on graphene composites for high performance structural applications under severe loading condition for instance the crashworthiness.

This work aims to derive a multiscale modelling of a hierarchical short glass fibres/graphene platelets/polymer composite materials for high performance applications in crashworthiness.
The solution of the heterogeneous material problem is obtained by using mean-field homogenisation schemes for instance the Mori-Tanaka based Digimat approach. This enables the computation of 2-phases graphene polymer composite that is used later as matrix phase for the 3-phases short glass fibres reinforced graphene polymer composite. Effective properties are therefore implemented in a multiscale finite element characterisation of tensile, compression and fracture toughness specimens as well as Charpy impact test for providing the damage/failure thresholds for crashworthiness purposes.

1. Mean-field homogenisation

For a macroscopic homogeneous and microscopic heterogeneous materials under a representative volume element RVE, the effective properties are given by:

$$C_{ijkl}^{eff} = \frac{1}{V}\int_V c_{ijmn}\left(r\right) A_{mnkl}\left(r\right) dV \tag{1}$$

Or in others terms

$$\boldsymbol{C}^{eff} = \sum_{I=0}^{N} f_I \boldsymbol{c}^I : \boldsymbol{A}^I \tag{2}$$

with $\boldsymbol{c}^I$, $\boldsymbol{A}^I$, f_I the uniform stiffness tensor, the global strain concentration tensor and the volume fraction of phase I respectively. Using, the Eshelby's inclusion concept [3], the final expression of the global strain concentration tensor is given such as:

$$\begin{cases} \boldsymbol{A}^I = \boldsymbol{a}^I : \left\langle \boldsymbol{a}^I \right\rangle^{-1} \\ \boldsymbol{a}^I = \left[\mathbf{I} + \mathbf{S} : \left(\boldsymbol{c}^0\right)^{-1} : \Delta \boldsymbol{c}^I \right]^{-1} \end{cases} \tag{3}$$

where $\boldsymbol{a}^I$ states for the local strain concentration tensor and $\Delta\boldsymbol{c}^I = \boldsymbol{c}^I - \boldsymbol{c}^0$. $\mathbf{S}$ represents the Eshelby's tensor [3]. Its expression depends on the aspect ratio $AR = c/a$ of the ellipsoidal inclusion of semi-axis $\left(a,b,c\right)$ and the properties of the surrounding matrix $\boldsymbol{c}^0$. Under the Mori-Tanaka MT [4] assumptions, the global strain concentration tensor of the matrix is expressed as [5, 6]:

$$\boldsymbol{A}^0 = \boldsymbol{a}^0 : \left\langle \boldsymbol{a}^I \right\rangle^{-1} = \left(f_0 \mathbf{I} + \sum_{I=1}^{N} f_I \boldsymbol{a}^I \right)^{-1} \tag{4}$$

leading to the effective MT properties through Eq. (2) such as:

$$\boldsymbol{C}^{MT} = \sum_{I=0}^{N} f_I \boldsymbol{c}^I \boldsymbol{A}^I = \left(f_0 \boldsymbol{c}^0 + \sum_{I=1}^{N} f_I \boldsymbol{c}^I \boldsymbol{a}^I \right) : \boldsymbol{A}^0 \tag{5}$$

2. Modelling strategy for the hierarchical composite

Analytical based homogenisation as well as finite element techniques are used to provide the composite with the effective response. This methodology as described by Figure 1. Indeed, the mechanical properties of the graphene which are widely derived at the atomistic scale [1, 2] are considered through graphene platelets GPL as continuum phases interacting with an elasto plastic polymer matrix. The composite response is therefore computed under a boundary value problem by applying static or kinematic admissible loading. Mean-field homogenisation schemes for instance the Mori-Tanaka based Digimat are applied to obtain the overall response. Several design parameters like the (2D aligned vs 3D random) graphene orientation as well as the uniform graphene sizes versus different graphene sizes and the aspect ratio (AR) effects are investigated. Numerical applications are performed by studying the graphene platelets clustering effects and volume fraction variation as well as the influence of Young modulus variation on the overall stress-strain response.

The modelling of 3-phases short glass fibres/graphene polymer composite is based on a double-scale approach combining the 2-phases graphene polymer composite developed as matrix phase in which are embedded the glass fibres. The derivation of the effective properties remains analytical-based micromechanics formalism. Results carried out on tensile, compression and fracture toughness specimens as well as Charpy impact test (Figure 1) through Finite element simulation enable the determination of the damage/failure thresholds for crashworthiness applications. The proposed constitutive law is therefore implemented within a finite element code as a user defined material subroutine (UMAT). Figure 2 depicts a full crash box simulation where at each Gauss integration point, the response of the 3-phases composite (2%graphene + 60% short fibres + 38% polymer PA) is compared with that of 2-phases composite (60% short fibres + 40% polymer PA) as well as the response provided by the steel.

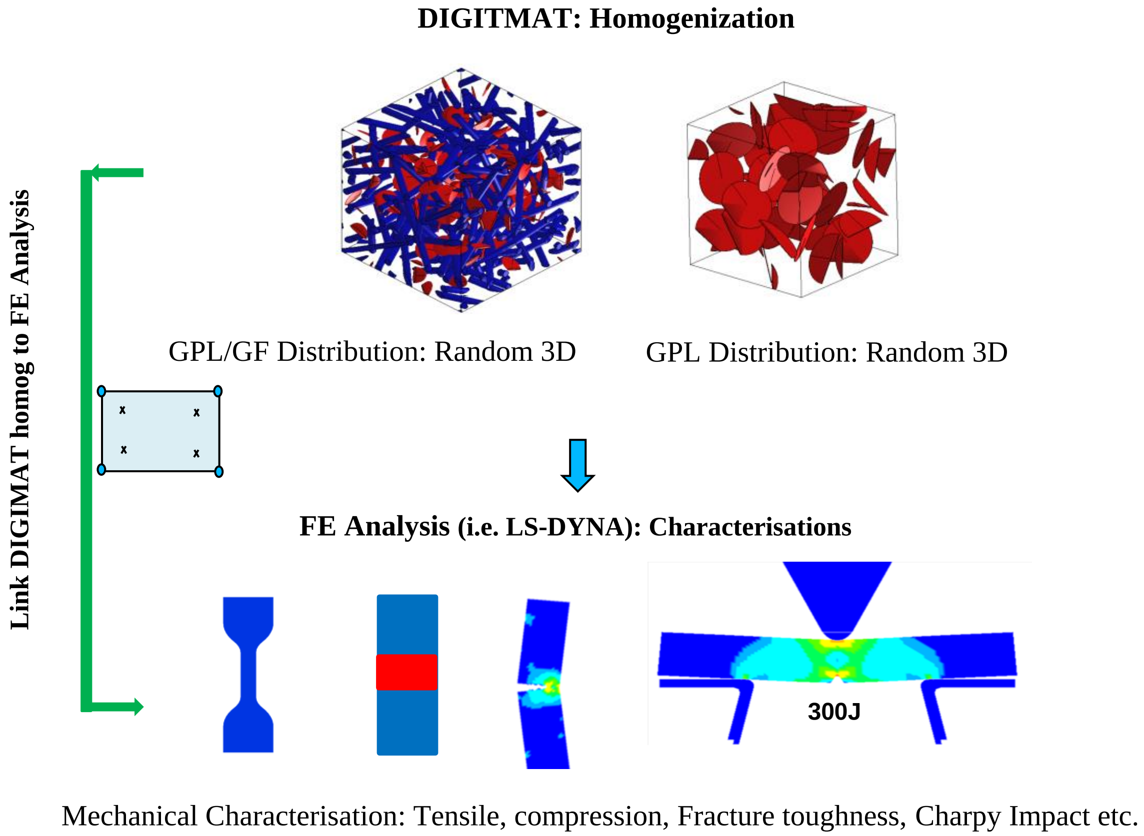

Figure 1: Modelling approach for the hierarchical short glass fibres/graphene polymer composite.

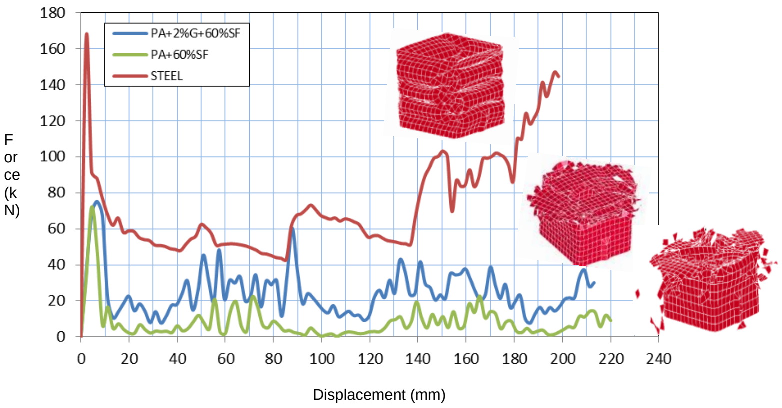

Figure 2: Force versus displacement for a full crash box simulation.

3. Conclusions

The response of a full crash box composite is analysed by considering a hierarchical modelling. The composite is made of short glass fibres that are embedded within a graphene reinforced polymer matrix. To determine the damage/failure thresholds for crashworthiness, analytical based homogenisation as well as finite element techniques are used. Results of simulation highlight the contribution of the graphene by decreasing the pick of force at the early stage of loading that represents an effective perspective in terms of safety for vehicles occupants.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Program under grant agreement no. **604391 Graphene Flagship**.

References

[1] J.R. Xiao, B.A. Gama, and J.W. Gillespie Jr. An analytical molecular structural mechanics model for the mechanical properties of carbon nanotubes. *International Journal of Solids and Structures*, 42: 3075 – 3092, 2005.

[2] J. Cho, J.J. Luo, and I.M. Daniel. Mechanical characterization of graphite/epoxy nanocomposites by multi-scale analysis. *Composites Science and Technology*, 67 (1112): 2399 – 2407, 2007.

[3] J. D. Eshelby. The determination of the elastic field of an ellipsoidal inclusion, and related problems. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 241 (1226): 376–396, Aug. 20, 1957.

[4] T Mori and K Tanaka. Average stress in matrix and average elastic energy of materials with misfitting inclusions. *Acta Metallurgica*, 21 (5): 571 – 574, 1973.

[5] P. Vieville, A. S. Bonnet, and P. Lipinski. Modelling effective properties of composite materials using the inclusion concept. general considerations. *Arch. Mech.*, 58 (3): 207–239, 2006.

[6] W.L. Azoti, Y. Koutsawa, A. Tchalla, A. Makradi, and S. Belouettar. Micromechanics-based multi-site modeling of elastoplastic behavior of composite materials. *International Journal of Solids and Structures*, 59: 198 – 207, 2015.