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Investigation of Mechanical Performance of Automotive Lighting Device under Random Vibration Loads

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Abstract
Predicting mechanical performance of thermoplastics is very important because stylistic and complex geometrized products are validated through OEM (Original Equipment Manufacturer) test standards, that product should promise a customer confident design and also satisfy a good lighting performance. Hence, headlamp design made of thermoplastics, mineral filled Polypropylene (PP) for body, Polycarbonate (PC) for outer lens and stylistic components, is investigated under random vibration loads supplied by OEM test standard and predicting mechanical performance of thermoplastics becomes very important. Tensile tests are utilized in predicting mechanical performance of materials, with dog bone type test specimens at 1mm/min tensile test speed. Design validation is achieved through finite element vibration simulations until initial injection moulded components are produced where design phase is finished by design validation tests. It is critical to characterize mechanical behaviour of thermoplastics as directly affected from injection pressure, design space (CAD geometry). Travel distance of thermoplastic material in design space affects mechanical performance. Increasing travel distance decreases mechanical performance of final product, also increase in injection pressure results in enhanced and tough product. Finite element vibration simulations performed with material data from dog bone type test coupon resulted in poor correlation with product validation tests. However, test coupon cut from moulded component and mechanical properties predicted through tensile tests has a very good correlation with design validation tests.

Keywords: Random Vibration, Finite Element Vibration Analysis, Automotive Exterior Lighting, Thermoplastic Materials, Uniaxial Material (Tensile) Tests

INTRODUCTION

Thermoplastics are widely used in Automotive exterior lighting products and in body elements. Also, in aviation instead of glass, being light, having good mechanical performance and ease in formability makes thermoplastics a strong alternative [1, 2]. Nevertheless, mechanical performance of thermoplastics is affected from injection moulding process like holding pressure, injection pressure, annealing time, warpage and several other parameters can be listed [1]. Due to the excess of the parameters that are effective in polymer injection moulding process, it is an optimization problem to prevent errors and to find out optimum production parameters. The Taguchi method is utilized to predict the factors that affect the quality of the product fast and requiring less experimental data [3-6]. Also, artificial neural networks with genetic algorithm is benefitted to optimize the melting temperature, mould temperature, injection time, holding time, holding time parameters [7]. Xu et al. (2015) [1] performed optimization of the production parameters with artificial neural networks in order to prevent the collisions in injection systems and to increase the impact strength of the polymer products. Shaharuddin (2006) [8] and Yang (2006) [9] studied carbon fibres and composites for parameter analysis. Desai et al. (2018) [10] used the optimization of injection parameters in medicine production. Khan (2016) [11], Singh (2017) [12] and Fernandes (2018) [13] published a summary study on the literature. Research effort is paid through identifying appropriate process parameters to have a high quality product with good mechanical properties. It is a must in numerical experimentation to include material data required to predict failure if present. Material models for plastics include single tensile or compression test data both for micro mechanical and macro mechanical deformation characteristics. In injection moulding process travel distance, injection and holding pressure like parameters effect deformation and failure behaviour of thermoplastics. Material models for thermoplastics can be separated into two main categories. Behavioural (phenomenological) models and models based on the foundations of polymer physics. Phenomenological model is based on macro mechanical behaviour of polymers. Models based on polymer physics focus on predicting macro mechanical behaviour by modelling micro mechanical behaviour at micro level (at the polymer bond level) [14, 15]. Wu et al. (1994) [16] conducted research on shear band in polymers and modelled the beginning and spread of the shrinkage occurring during high deformations with finite elements. Boyce (1995) [15] focused on the effects of initial defects, strain softening, edge effects and deformation rate. In this study, effects of injection pressure and travel distance of mould will be investigated for a complex and stylistic geometry made of Polycarbonate (PC) material to predict failure. Injection moulding process of complex geometries include different parameters effecting mechanical performance, material parameters for a test coupon of simple geometry do not always predicts enough information about failure characteristics of thermoplastics. Hence two different type test specimen used in this study, one cut from Bezel to include travel distance effects and other is dog bone type tensile test specimen. Mechanical properties of PC material are identified through tensile test data at 1mm/min of deformation rate with both dog bone type tensile test specimen and test coupon cut from Bezel [17, 18]. Material data obtained, utilized in finite element random vibration simulations, and effects of travel distance, injection and holding pressure effects identified both with numerical experimentation and real life vibration tests. Even though no failure predicted in numerical experimentation with material data observed from dog bone type tensile test specimen, design failed in real life random vibration tests. Unpredicted failure is due to mechanical characteristics of PC material which changed during injection moulding process. Test coupon cut from bezel, stylistic component of headlamp assembly, validated degradation in mechanical properties. Toughness of PC material %10 changed with increasing injection pressure however increasing travel distance halved tensile yield strength.

MATERIALS AND NUMERICAL EXPERIMENTATION

Automotive headlamp design includes many stylistic components which are mostly made of PC material and design of all assembly is driven by finite element vibration, assembly and injection moulding simulations. Decisions made through numerical experimentation in design phase are validated in real life vibration tests and quality of injection process by try-out. Bezel, investigated in this study, reflector and like elements are all included in headlamp assembly and must satisfy a regulated light pattern and customer demands. Headlamp assembly have certain inputs to achieve regulated light pattern, however for customer demands the only criteria is to design a failsafe headlamp assembly. That is, mechanical performance of the material used in design phase should in detail be investigated and effects of process parameters to be known.

Mechanical performance for PC material decided through tensile test at 1 mm/min with dog bone type tensile test specimen shown in Fig.1.

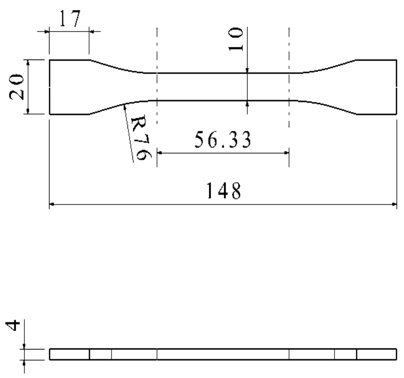

Figure 1. Tensile test specimen.

Tensile yield stress and yield strain for PC material through test data are 17.14 MPa and 0.006634 mm/mm respectively, shown in Fig.2 in terms of true stress versus true strain. Injection and holding pressure used in the injection process of dog bone type tensile test specimen are 200 and 100 MPa respectively. However, travel distance effects are not included as dog bone type specimen have certain dimensions and also no complexity is present in geometry to effect mechanical characteristics.

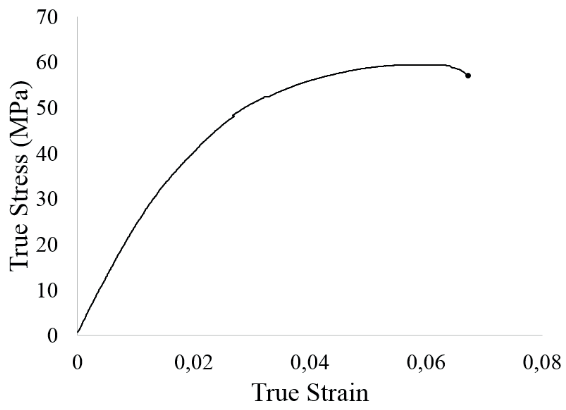

Figure 2. Material tensile test data for PC material at 1 mm/min.

Mechanical characteristics for dog bone type test specimen and test specimen cut from material shown in Fig. 3. In linear elastic behaviour significant difference is present for PC material. Tensile yield stress halved on test specimen cut from Bezel. Nevertheless, increase of almost %10 percent on tensile ultimate stress is observed.

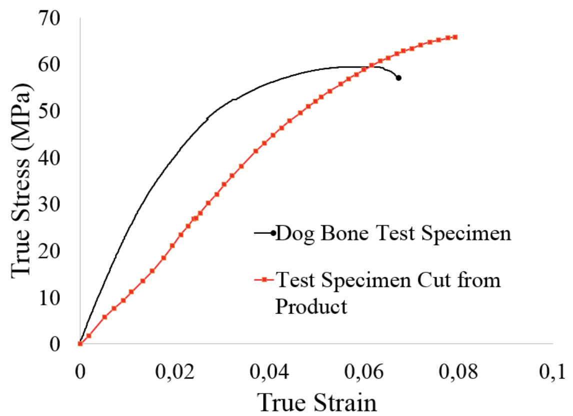

Figure 3. Material characteristics for PC from dog bone test specimen and test coupon cut from product.

Effect of holding pressure on mechanical properties of PC material shown in Fig. 4 at different holding pressures. Increasing holding and injection pressure on test coupon do not significantly change the yield stress for PC material [19]. Nevertheless, toughness also does not show significant change for PC at different holding pressures, it has only %10 of increase against 55 MPa of rise in holding pressure.

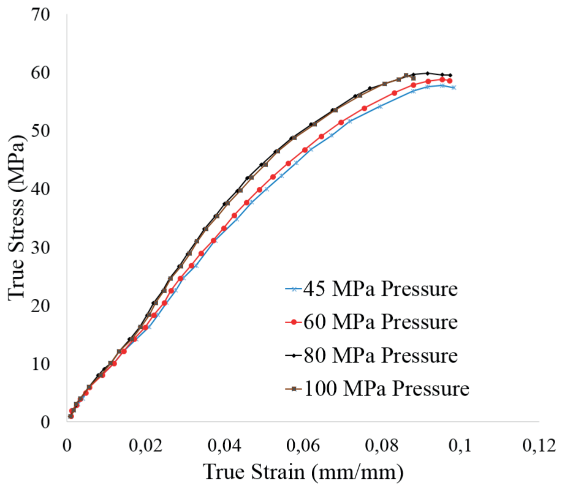

Figure 4. Tensile properties of PC material at different holding pressures.

Injection moulding process of large geometries, in Bezel width is almost 380 mm and height is 700 mm, show significant differences on mechanical performance as the larger the geometry is the more the design parameters effects material's mechanical properties. Test coupon cut from different locations of Bezel shown in Fig. 5 to identify travel distance effect on mechanical properties. Travel distance from Location I to Location VI is, 147mm, 271mm, 120mm, 76mm, 180mm and 185mm respectively.

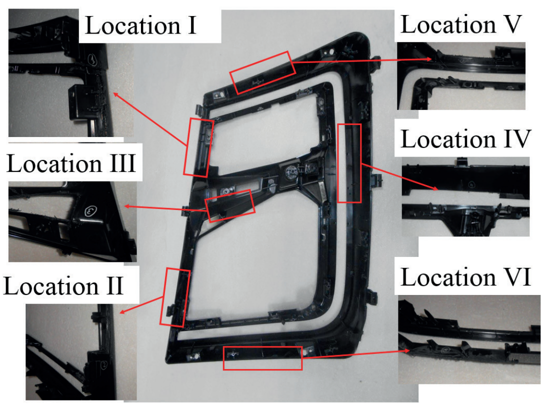

Figure 5. Locations of test coupon cut from Bezel with different travel distance.

Tensile test performed at 1 mm/min, results for each coupon shown in Fig. 6. The highest performance obtained with coupon cut from Location IV with travel distance of 76 mm, and the lowest performance predicted with test coupon cut from Location II with travel distance of 271 mm.

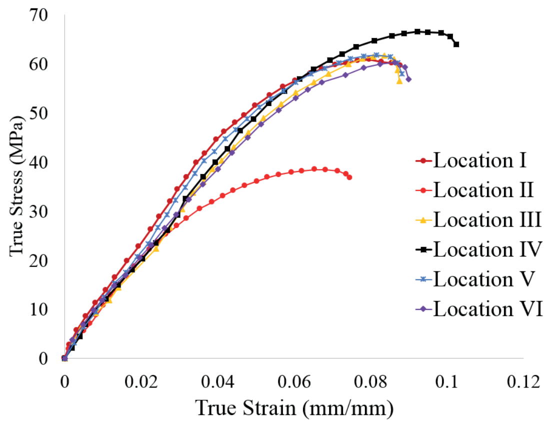

Figure 6. Travel distance effect on mechanical performance predicted through tensile tests.

In tensile yield stress, except for location II, almost no change observed. However, in location II, highest travel distance is present, vast decrease in yield stress observed. Yield stress change against test coupon location shown in Fig. 7. Decrease in mechanical performance was expected. However, in Location II it is degradation, called burn of thermoplastic material in design space due to large travel distance and heat in mould.

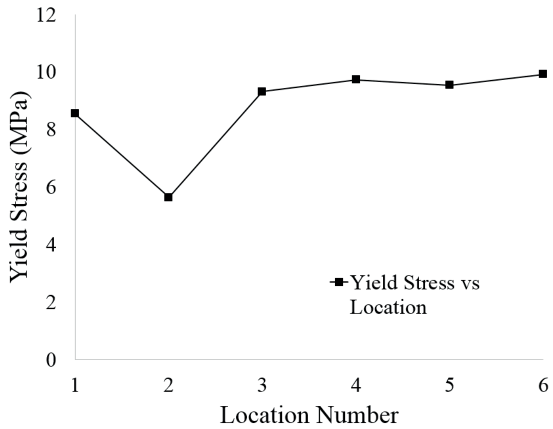

Figure 7. Travel distance effect on yield stress for each location.

In failure prediction, tensile test data is utilized considering stress and strain values exceeding the yield stress and strain. Insufficient knowledge of mechanical performance about material make the analyst to predict no failure, and this consequence with poor design considerations and also loose in customer confidence if any unpredicted failure occurs.

Finite element model and assembly strategy for bezel shown in Fig. 8. Numbers indicate assembly locations of the component in headlamp. Headlamp assembly have 73601 elements and 74619 nodes defined for finite element random vibration calculations. Bezel include 9953 elements and 10310 nodes in finite element model.

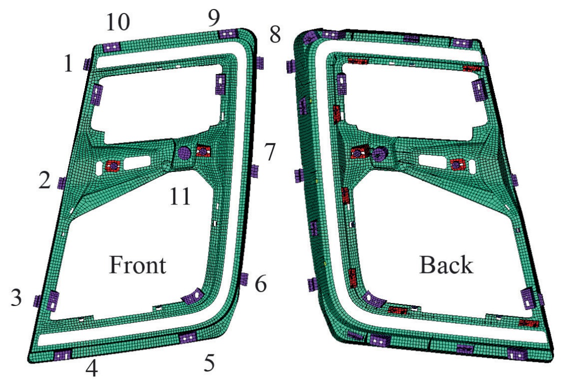

Figure 8. Bezel, stylistic component of headlamp made of PC.

Finite Element Random Vibration Simulations

Random vibration is a frequency domain approach to dynamic problems, that differential equation of motion in time domain is transferred into frequency domain. In frequency domain approach to dynamic problems reduces solution time, cost and data storage limits. Dynamic loads in random signals for a dynamic problem in time domain cannot easily be solved, as time signal is complex and nonlinear, however considering random signal as sum of different sine signals at different frequencies, which makes easy to transform a random time signal into a frequency based load vector, differential equation can be handled in frequency domain.

Transformation of differential equation of motion from time domain to frequency domain is predicted in Eq. 1 to Eq. 7.

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{F(t)\} \quad (1)$$

{x (t)} is the displacement vector, [M], [C] and [K] are mass, damping and the stiffness matrix respectively and {F (t)} is load vector.

$$x(t) = X.e^{i\omega t} \quad (2)$$

$$F(t) = F.e^{i\omega t} \quad (3)$$

Displacement and load vectors are both predicted in frequency domain in sinusoidal form in Eq. 2 and Eq.3. Hence, velocity and acceleration components of displacement can be obtained by differentiating Eq.2 with respect to time, replacing velocity and acceleration components into differential equation and making simplifications results in frequency domain form of differential equation of motion, in Eq. 4 and Eq.5.

$$X(\omega) = H(\omega).F(\omega) \quad (4)$$

H (ω) is the transfer function in terms of frequency, and explicit form of transfer function is predicted in Eq.5;

$$H(\omega) = [-[M].\omega^2 + [C].\omega.i + [K]]^{-1} \quad (5)$$

X (ω) is the vector of displacement amplitude and F (ω) is the vector of force amplitude [20, 21]. Matrix of the loading power spectral density (PSD) functions for random loads can be generated by applying the Fourier transformation to the load vector {F (t)}.

$$[D_{xx}(\omega)] = \begin{bmatrix} D_{11}(\omega) & \cdots & D_{1m}(\omega) \\ \vdots & \ddots & \vdots \\ D_{1m}^{*}(\omega) & \cdots & D_{mm}(\omega) \end{bmatrix} \quad (6)$$

Diagonal terms $D_{ii}(\omega)$ are auto correlation functions of load {F(t)} and the off diagonal terms $D_{ij}(\omega)$ are cross correlation functions of load $\{F_i(t)\}$. Then system of domain differential equation of motion in time domain, Eq.1, reduces to its frequency based form expressed in Eq. 7.

$$[D_{\sigma}(\omega)]_{nxn} = [H(\omega)]_{nxm}.[D_{xx}(\omega)]_{mxm}.[H(\omega)]_{mxn}^{T} \quad (7)$$

Solution of Eq. 7 predict frequency domain characteristics of dynamic problem and makes analyst decide on failure of design or any component in the assembly considered during finite element random vibration simulations.

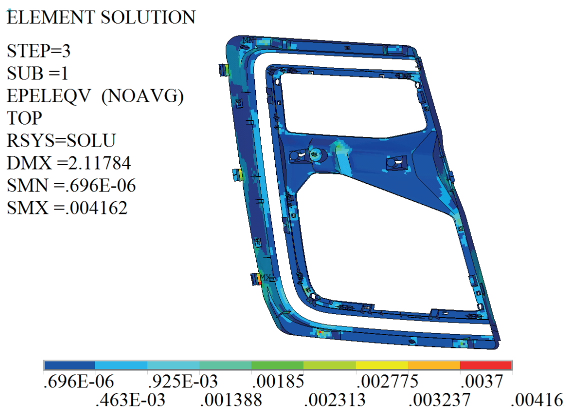

Figure 9. Equivalent Strain distribution from Finite Element Random Vibration in X axis with material data from dog bone type tensile test specimen.

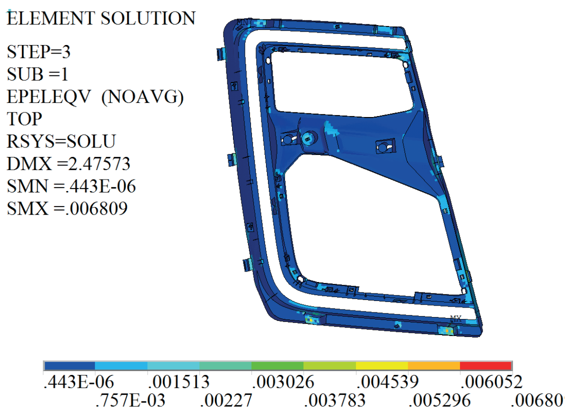

Figure 10. Equivalent Strain distribution from Finite Element Random Vibration in Y axis with material data from dog bone type tensile test specimen.

In Fig. 9 finite element vibration simulation results in terms of equivalent strain for bezel is illustrated, material data for PC is observed from dog bone type tensile test specimen predicting no failure as crack initiation value (tensile yield strain) is 0.006634 mm/mm. Dog bone type tensile test specimen include no defects due to injection moulding process like material degradation because of travel distance. Travel distance effects residual stress distribution due to solidification at different ratios because of complex nature of design. Filling stages of injection moulding process and solidification ratio on Bezel shown in Fig. 11 and Fig. 12 respectively.

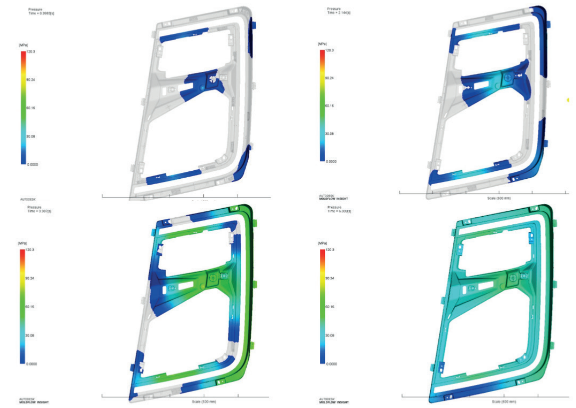

Figure 11. Filling stages of Injection Moulding Process.

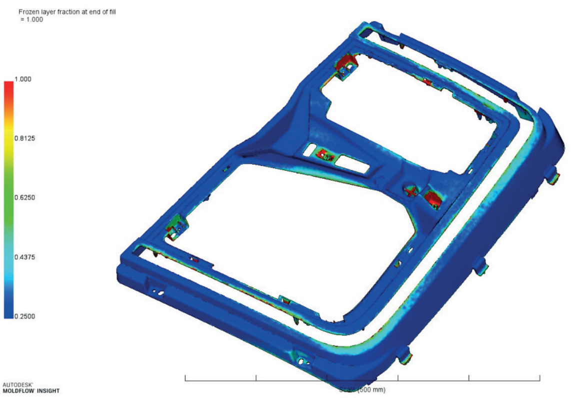

Figure 12. Fraction of solidification in Bezel after Injection moulding.

Material data predicted utilizing tensile test coupon cut from Bezel includes deficiencies from injection moulding process, effecting mechanical performance of PC. Tensile test results including process effects predicts failure at lower stress values, crack initiation limit is 9 MPa. Degradation on mechanical characteristics of material noticed in real life vibration tests, with failure on almost all assembly locations of Bezel. Failure results from vibration test shown in Fig. 13, belongs to injection pressure of 180 MPa and 50 MPa of holding pressure and in Fig. 14 injection pressure is 180 MPa and holding pressure increased to 70 MPa.

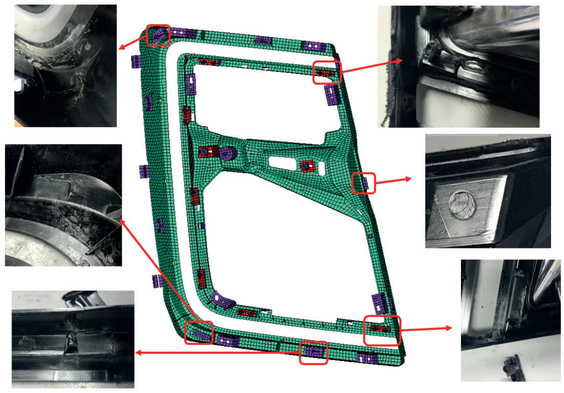

Figure 13. Failure after vibration test of Bezel with 180 MPa of injection pressure and 50 MPa holding pressure.

Reduction in failure locations observed because of increase in holding pressure thus toughness of final product. However, in dog bone type tensile test specimen toughness change was about %10 percent, hence almost no effect obtained as result of simple geometry. In complex geometries small increase in holding pressure increases toughness and deformation characteristics of design.

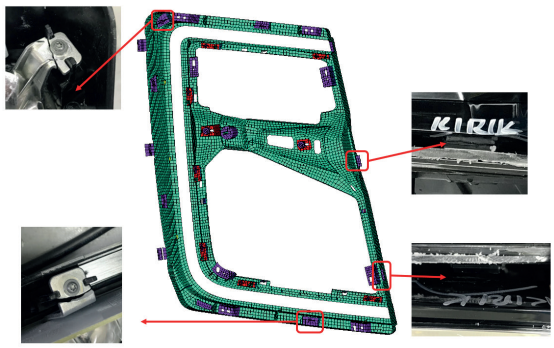

Figure 14. Failure after vibration test of Bezel with 180 MPa of injection pressure and 70 MPa holding pressure.

Test coupon cut from bezel has 180 MPa injection pressure and 50 MPa holding pressure in injection moulding process. Hence, finite element random vibration simulations performed with material data at 50 MPa of holding pressure and comparison of results is going to be achieved with failure investigated in Fig. 13. Material data including travel distance effect divided into six different locations for test coupon cut from Bezel. Locations for test coupon and material data were previously mentioned in Fig. 5 and Fig. 6 respectively. Material mapping of Bezel, hence, material definition in finite element random vibration simulations is shown in Fig. 15.

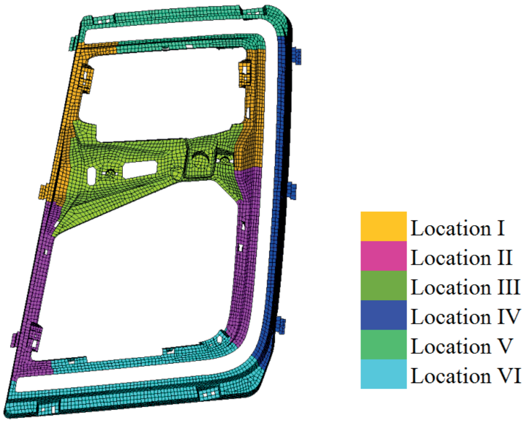

Figure 15. Material mapping of Bezel considering travel distance effect on mechanical performance.

Correlation among finite element analysis results and tests are fairly good in capturing failure locations. Finite element random vibration simulation results for equivalent stress distribution are shown between Fig. 16 to Fig. 19. In Fig. 17 and Fig. 18 stress distribution is restricted between yield stress and maximum stress predicted in finite element random vibration simulation.

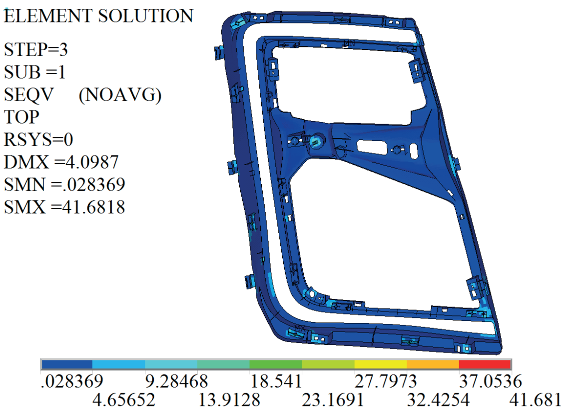

Figure 16. Equivalent Stress distribution from Finite Element Random Vibration in X axis with material data obtained from test coupon cut from Bezel.

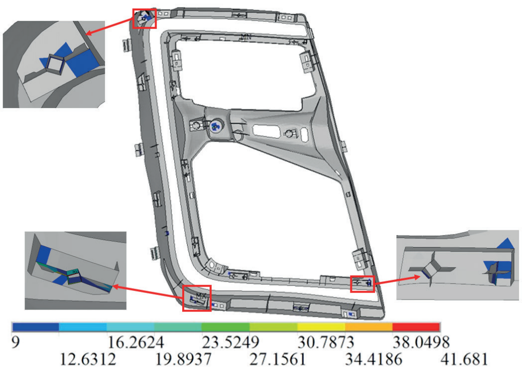

Figure 17. Failure definition through Finite Element Random Vibration in X axis with restricting stress values between yield stress and maximum stress from finite element simulation.

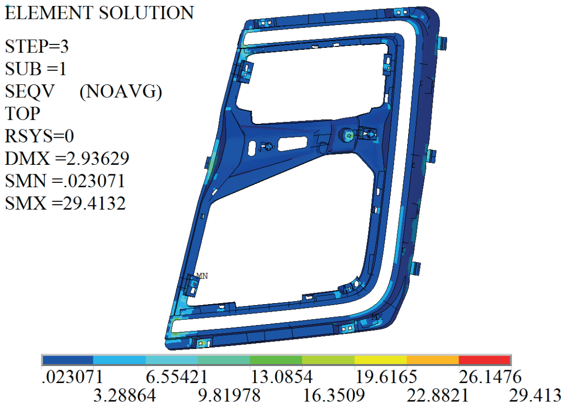

Figure 18. Equivalent Stress distribution from Finite Element Random Vibration in Y axis with material data obtained from test coupon cut from Bezel

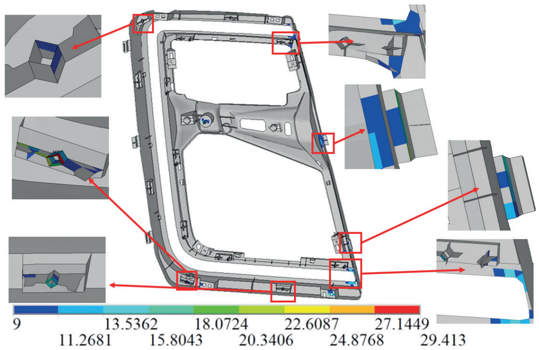

Figure 19. Failure definition through Finite Element Random Vibration in Y axis with restricting stress values between yield stress and maximum stress from finite element simulation.

RESULTS and DISCUSION

Mechanical performance of PC material investigated with tensile tests at 1 mm/min with dog bone type tensile test specimen. In dog bone type tensile test specimen, no geometrical effect is present and mechanical properties are 17.14 MPa of yield stress and 0.006634 mm/mm of yield strain. However, mechanical properties predicted with test coupon cut from product, possessing injection moulding process effects halved tensile yield stress for PC and a vast difference in linear elastic behaviour observed. To predict injection moulding effect on mechanical performance, in terms of travel distance, test coupon cut from 6 different locations of Bezel tested at 1 mm/min deformation rate. It is observed that increasing travel distance results in degradation of mechanical performance of thermoplastic, namely PC. However, in linear elastic behaviour tensile yield stress is almost constant for all the specimen except the one with maximum travel distance. Travel distance is predicted through filling stage of design space in injection moulding process and results with solidification difference in design space, hence mechanical and deformation characteristics of thermoplastic differs. Material properties from dog bone type tensile test specimen do not supply sufficient knowledge in failure prediction. Because of simple geometry, effect of process parameters like travel distance and holding pressure have no consequence on capturing material degradation in mechanical properties of PC. Complex nature of stylistic components in headlamp design includes deficiencies due to injection moulding process parameters like injection and holding pressure, component size (travel distance). Injection and holding pressure effect predicted through dog bone type tensile test specimen at different holding pressure values identified with tensile tests at 1mm/min deformation rate. In linear elastic behaviour, in terms of yield stress, almost no difference is observed only toughness slightly changed at %10. However, in complex geometries holding pressure effect on material properties identified in real life vibration tests, having difference in failure characteristics. Mechanical performance of PC material investigated in terms of tensile test properties for dog bone type tensile test specimen and test coupon cut from product. Predicted material data utilized in finite element random vibration simulations. Tensile test data from dog bone type specimen with identified yield stress and strain, predicted no failure in finite element random vibration simulations. Hence forth, material data is not capable of predicting process effect on mechanical properties. In finite element random vibration simulations by material data predicted with test coupon cut from Bezel, with injection and holding pressure of 180 MPa and 50 MPa respectively, failure definition in all assembly locations of Bezel in real life vibration tests are captured. Real life vibrations tests are performed with Bezel at 180 MPa and 50 MPa of injection and holding pressure respectively.

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