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Design of a Ballistic Composite Cover Plate for Armoured Fighting Vehicles

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Abstract

Armoured fighting vehicles such as Main Battle Tank (MBT) operate in a variety of theatres right starting from desert, marshes to high altitude areas. To deploy and operate such platforms, strategic, tactical and battlefield mobility have to be higher, for which combat mass of the platform is a critical parameter. To keep this parameter within optimum limits, overall mass reduction of the platform is crucial, which is also challenging as the structure has to offer not only strength and rigidity but also ballistic protection. This challenge is further complicated if the panel or component is exposed to high temperature.

This paper tries to address these design challenges through a case study, wherein a composite cover plate made of Ceramic tiles, Kevlar, Foam with stainless steel sheets as backings in a sandwich construction is presented. The complete design and iteration methodology is first explained in detail along with constraints. Subsequently, the modelling process and creation of lay and stackup is presented along with mesh creation and validation. This is then followed by a static structural, modal, random vibration, shock response spectrum, thermal and explicit dynamic analysis. Although, all the above FE results are presented, only the final results are discussed and the complete iteration process stepwise for each analysis is neglected. Finally, it is observed that by careful selection of materials, configuration, layup and stackup, it is possible to design a cover plate to withstand severe loading conditions and achieve a mass saving of approximately 35-40%. This FE study was generated, executed and post-processed using ANSYS Workbench software with ACP-Pre and ACP-Post solvers.

Introduction

As the threat scenario for armoured fighting vehicles such as Main Battle Tank (MBT) are evolving, their deployment and role have undergone a phenomenal change. From a platform that was exploited for pure state-to-state warfare, these platforms are currently expected to excel in both urban and semi-urban environments. Another contemporary challenge is the deployment in high altitude areas. As MBTs cannot be transported by road and rail to these terrains, air deployment is the only left out option. In such a scenario, the future qualitative requirements are expected to include weight, over dimensioned consignment for aircrafts etc., as mandatory parameters in addition to others.

When such imposing constraints are included in the design paradigm, the traditional lethality based design is reversed which now includes weight as the header [1]. To achieve this, weight reduction in each component, sub-system, system & structure is mandatory. This paper tries to address this design challenge of weight reduction of structures through a case study. This case study pertains to a cover plate that is used to cover the rear portion of the powerpack (integrated engine cum transmission) on the hull of a MBT as shown in Figure 1.

This cover plate has the following functions.

a. Provide ballistic protection to the powerpack from armour piercing small arms ammunition and shrapnel to NATO Standard STANAG 4569 Level-II.
b. Seal the powerpack compartment from dust ingress during operation in desert terrain.
c. Seal the powerpack compartment from water ingress during fording operation and rain.
d. Provide cooling air venting for twin cooling fans provided on the top of the transmission through the louvres.
e. Provide ease of inspection such as oil and coolant level checking.
f. Provide attachment points for locating tools.

To achieve the above objectives, the contemporary cover plate is made of rolled homogenous armour steel with 18 mm thickness to provide ballistic protection. In order to achieve sealing, a nitrile rubber gasket is provided namely on the periphery between the rear cover plate and the side plate, rear plate and middle cover plate interface. The overall mass of this rear cover plate is around 220 kg and the design objective is to achieve a minimum mass saving of 33%, without

FIGURE 1 Rear Cover Plate for Powerpack on MBT

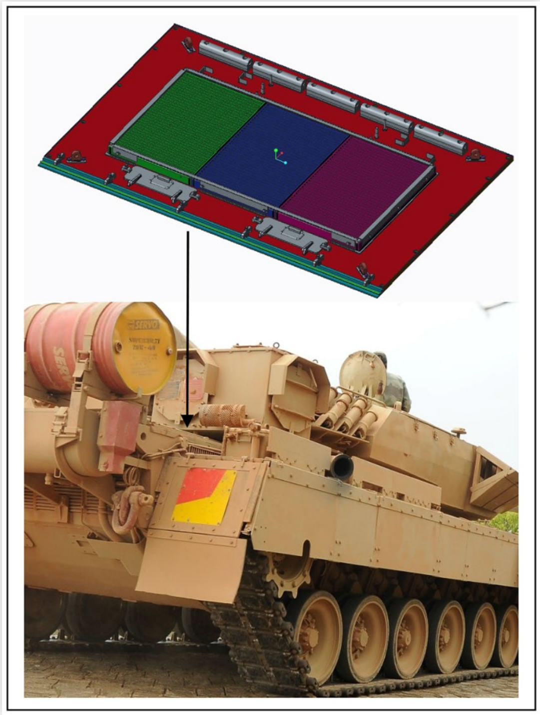

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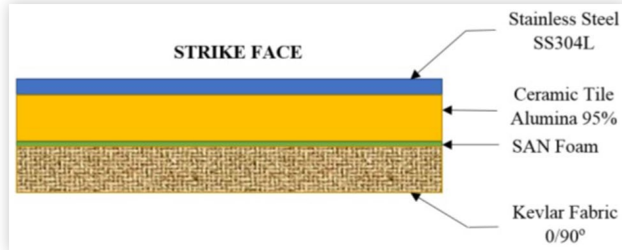
FIGURE 2 Composite configuration for cover plate



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compromising on protection and functionality aspects. This paper intends to demonstrate the methodology employed for designing the rear cover plate of a MBT using ballistic composites. The design methodology is validated by a FEA study that includes static structural, modal, random vibration, shock response spectrum, thermal and explicit dynamic analysis which are given as follows.

Design Methodology

The first and foremost in the design process is the modelling of the base plate so that interfacing components and holes match with that of the hull structural plates. This base plate is the top plate that is composed of Stainless Steel (SS) to AISI 304L. Since this grade of stainless steel has very good corrosion resistance and weldability it is chosen for the design. On the bottom of this SS plate, the composite stackup is to be created for which a reference plane is created having the same contour. Once this modelling is completed, the assembly is imported as shells and solids to ANSYS Workbench to carry out composite analysis. The first step in the composite analysis is the material assignment, which is followed by the creation of a coordinate system exclusively for the composite stackup. Since, the reference coordinate system may not match with the stackup orientation, this step is necessitated as the stackup has to grow in either +Z or -Z only. On completion of this step, the stackup is created as shown in Figure 2.

In this configuration the strike face is the one on which projectile impact happens. As lot of add-ons such as lugs, brackets, lifting hooks etc., are welded to this plate, SS 304L is chosen as the top plate. To withstand ballistic impact, ceramic tile made of 95% alumina is chosen. The ceramic tile has high hardness of 12.5 HV at 0.5 kg. It is this hardness, that is primarily responsible for preventing projectile penetration through three modes [2]. Firstly, the ceramic tile blunts the projectile initially upon impact. Secondly, it encourages ricochet effect or deflecting the projectile away upon impact. Finally, it encourages brittle failure or deformation in the projectile or penetrator. But a pure ceramic tile is of brittle nature and hence if not properly backed by an energy absorption material may fail which necessitates the use of Styrene Acrylonitrile (SAN) foam.

However, even this combination of ceramic & SAN if not backed by a stackup of high tensile strength material may fail or cause penetration, which necessitates the use of Kevlar bidirectional fabric (0/90°) which is a proven bullet proof material. The point to be noted is that if this configuration is inversed i.e. the Kevlar in the strike face then penetration does happen as it lacks hardness.

The next step in the design process on finalization of configuration is meshing, which is followed by the application of loads and constraints. Finally, six different analysis starting from static structural to explicit dynamics is performed to validate the design as shown in Figure 3 above. If the stresses during analysis are close to the yield or ultimate strength, the design iteration process has to be run with different set of configurations. This may result in either increasing the thickness of the ceramic tile or increasing the number of lays in the stackup. Of these two approaches, the later is preferred as mass is one of the chief constrains of the design. The exact material models, load cases, meshing, and various analysis are explained in detail in the forthcoming sections.

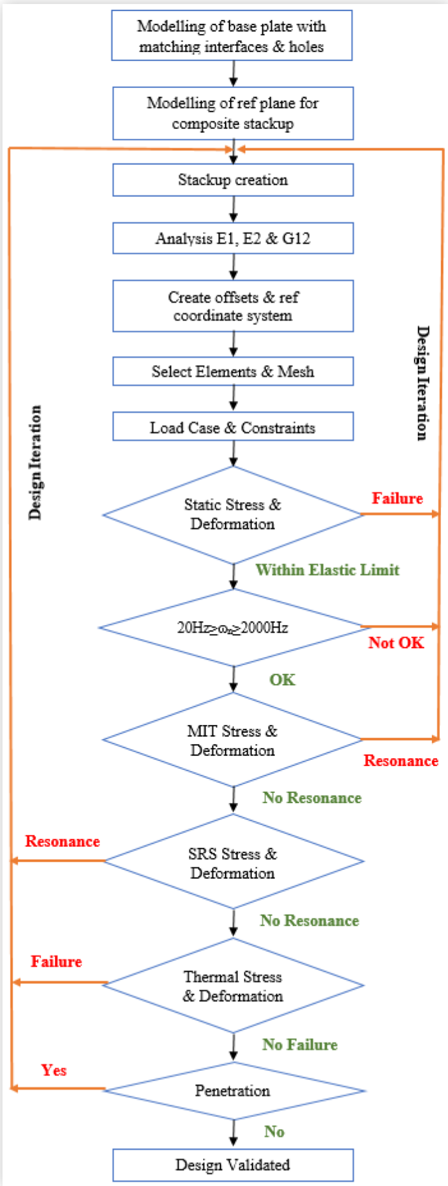
Material Model

With regard to static structural, modal, random vibration, Shock Response Spectrum (SRS) & thermal analysis linear material models are used. The isotropic properties for materials other than Kevlar and orthotropic properties of Kevlar are shown in Tables 1 and 2.

Whereas linear material models are used as discussed above, for the bullet penetration studies using explicit dynamics four different high strain rate material models are used.

a. For SS 304L: Steinberg-Guinan Strength Model [7], in which while yield stress initially increases with strain rate, at high strain rates (greater than 10^5sec-1) strain rate effects become insignificant and the yield stress

FIGURE 3 Flowchart for Design Methodology



reaches a maximum value which is subsequently strain rate independent. Shear modulus increases with increasing pressure and decreases with increasing temperature which includes Bauschinger effect. The constitutive relations for shear modulus G and yield stress Y are:

$$G = G_0\left\{1+\left(\frac{G_p'}{G_0}\right)\frac{p}{\eta^{1/3}}+\left(\frac{G_t'}{G_0}\right)(T-300)\right\}$$

$$Y = Y_0\left\{1+\left(\frac{Y_P'}{Y_0}\right)\frac{P}{\eta^{1/3}}+\left(\frac{G_\tau'}{G_0}\right)(T-300)\right\}(1+\beta\varepsilon)^n \quad (1)$$

$$\text{subject to } Y_0\left[1+\beta\varepsilon\right]^n \le \text{Ymax}$$

b. For Ceramic Tile & SAN Foam: Shock Equations of State (EOS) Linear [8], which is Mie-Gruneisen EOS based on Shock Rankine-Hugoniot equations.

TABLE 1 Linear Material Properties for SS, Ceramic & SAN Foam [3, 4, 5]

Properties	SS	Ceramic Tile	SAN Foam
Density in g/cc	8.00	3.74	0.103
Yield strength in MPa	210	--	--
Ultimate Strength in MPa	564	2000	80
Modulus of Elasticity in GPa	200	325	0.085
Poisson Ratio	0.30	0.230	0.30
Thermal expansion coefficient in strain/K	15.4 E-6	7.50 E-6	70 E-6
Specific heat capacity in J/g°C	0.423	0.880	1.18
Thermal conductivity in W/m-K	13.80	21.00	0.15

TABLE 2 Linear Material Properties for Kevlar [6]

Properties	Kevlar
Density in g/cc	1.40
Youngs Modulus in GPa: $E_1(0°)/E_2(90°)$	30/30
In-Plane Shear Modulus in GPa: G_{12}	5
Major Poisson Ratio: v_{12}	0.20
Ultimate Tensile Strength in MPa: X_t (0°)/Y_t (90°)	480/480
Ultimate Compressive Strength in MPa: X_c (0°)/Y_c (90°)	190/190
Ultimate In-Plane Shear Strength in MPa: S	50
Ultimate Tensile Strain in %: e_{xt} (0°)/e_{yt} (90°)	1.60/1.60
Ultimate Compressive Strain in %: e_{xc} (0°)/e_{yc} (90°)	0.60/0.60
Ultimate In-Plane Shear Strain in %: e_s	1.00
Thermal expansion coefficient in strain/K: α_1 (0°)/α_2 (90°)	7.4 E-6/7.4 E-6
Specific heat capacity in J/g°C	1.42
Thermal conductivity in W/m-K	0.04

The Shock EOS model includes quadratic shock velocity, particle velocity relation as given below.

$$U_s = C_0 + S_1 u_p + S_2 u_p^2 \quad (2)$$

For SS, both material models a & b are used together for computation.

c. For Kevlar: Puff EOS [9], which is based on Mie-Gruneisen form but with variable Gruneisen Gamma in the expanded phase to give the required convergence to perfect gas behavior at very large expansions if the energy e (ρ = ρ0) is greater than the sublimation energy e_s.

d. For Steel 4340: Johnsons Cook Model [10], used for the bullet penetrator is based on strain (work hardening), strain rate and thermal softening. In this model yield stress is given as,

$$Y = \left[A + B\varepsilon_p^n\right]\left[1 + C\ln\varepsilon_p^*\right]\left[1 - T_H^m\right] \quad (3)$$

Based on the above material models, the input parameters and constants for the various materials are given in Table 3.

TABLE 3 Explicit Material Properties [11]

Materials	Parameters & Constants
Stainless Steel 304L	Y_o: 340 MPa
	Y_{max}:2500 MPa
	β: 43
	n: 0.35
	G'_p: 1.74
	G'_T: -35.04 MPa/°C
	Y'_p: 0.007684
	T: 2106.9°C
	G_o: 77000 MPa
	Gruneisen Coeff: 1.93
	C_0: 4570 m/s
	S_1: 1.49
	S_2: 0 s/m
Ceramic Tile	Gruneisen Coeff: 0.5
	C_0: 6900 m/s
	S_1: 1.45
	S_2: 0 s/m
SAN Foam	Gruneisen Coeff: 1.18
	C_0: 2746 m/s
	S_1: 1.319
	S_2: 0 s/m
Kevlar	A_1: 8210 MPa
	A_2: 70360 MPa
	Gruneisen Coeff: 0.35
	Expansion Coeff: 0.25
	e_s: 8.23 E6 J/kg
	Erosion strain: 1.2
	Shear Modulus: 1000 MPa
	P_{min}: -150 MPa
Steel 4340	A: 792 MPa
	B: 510 MPa
	n: 0.260
	C: 0.140
	m: 1.030
	T_m: 1793 K

Composite Stackup for Analysis

The first step in the creation of composite stack up is the creation of individual ply or lamina. For this analysis, a single stackup made of Kevlar bidirectional ply of thickness 0.33 mm is used. Once thickness is determined and ply created, the next step is the creation of a stack up for which ply orientation is required. In this regard two methods namely symmetric and anti-symmetric stack ups are available. As anti-symmetric stack ups have a non-zero bending extension coupling which during fabrication induces thermal forces during curing & subsequent cooling [12], a symmetric orientation stack up is selected for this analysis. For this symmetric stack up, the orientation selected is [0/+45/-45/90/-45/+45/0] as is commonly used [13]. With this, the overall thickness of stackup is around 12 mm. The overall property of Kevlar stackup & laminate are shown in Figures 4 and 5. From this data it is observed that the laminate stiffness E_1, E_2, and laminate shear stiffness G_{12} have increased in all directions compared to a single ply indicating the efficacy of the stack up process.

FIGURE 4 Properties of single Kevlar ply

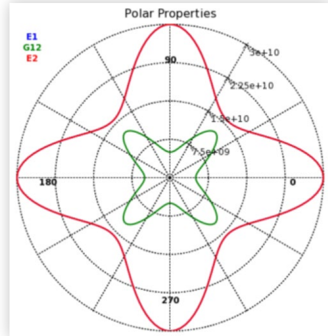
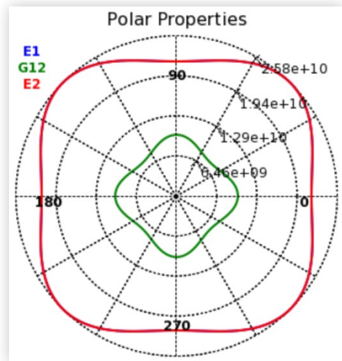


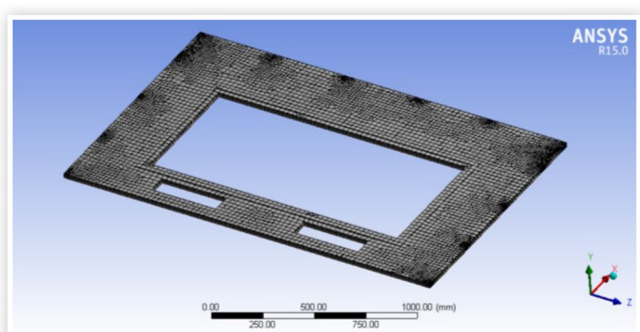
FIGURE 5 Properties of Kevlar Laminate



Meshing

Once stackup sequence & laminate creation is completed, the next step is meshing. This is critical, as bad meshing may give erroneous results. The meshed cover plate model is shown in Figure 6 and the mesh quality is shown in Figure 7. As the skewness ratio is 0.80 which is below the threshold of 0.95, the mesh quality is acceptable.

FIGURE 6 Meshed model of cover plate



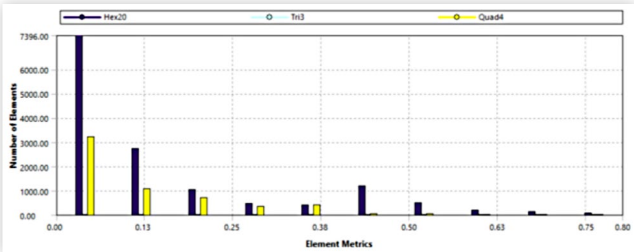


FIGURE 7 Mesh Quality - Skewness Ratio

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Static Structural Analysis

For the static structural analysis, the load case consists of the following.

a. Self-mass of the cover plate.
b. Louvre mass of 200 kg on the inner periphery.
c. Mass of 150 kg supposed of two men to perform maintenance standing on the top of the cover plate.

Similarly, the constraints consist of the following.

a. Fixed support of 40 mm width along the periphery - mounting surface.
b. Fixed support in the 14 holes of 24 mm inner diameter - mounting bolts location.
c. Fixed support beneath the louvres in the vertical direction - support given by the face seal between transmission and cover plate.

With the above loads & constraints the Von Mises stress and total deformation obtained are shown in Figure 8.

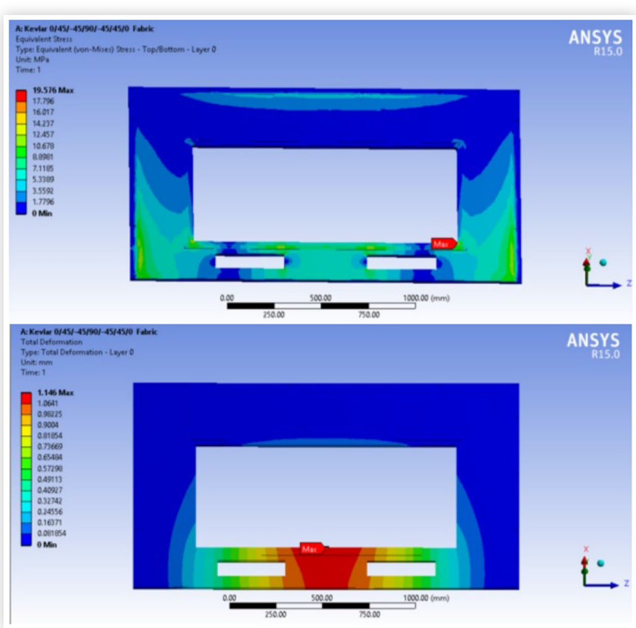

FIGURE 8 Static Structural Stress & Deformation

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Modal Analysis

Modal analysis is carried out to determine the natural frequency of the cover plate. This is critical to ensure that resonance does not occur when the excitation from the terrain, structure or systems coincide with the natural frequency of the cover plate. The safe range for the cover plate fundamental mode is either below 20 Hz or above 2000 Hz. The first 10 modal frequency values are shown in Figure 9.

Minimum Integrity Test (MIT) Analysis

The MIT is also known as the random vibration test is also a test to qualify the structural integrity of the system or component [14], the profile of which is shown in Figure 10. The PSD values shown are used as inputs in addition to the previous modal analysis results to carry out a random vibration analysis the results of which are shown in Figure 11.

FIGURE 9 First Ten Modal Frequencies for Composite Cover Plate

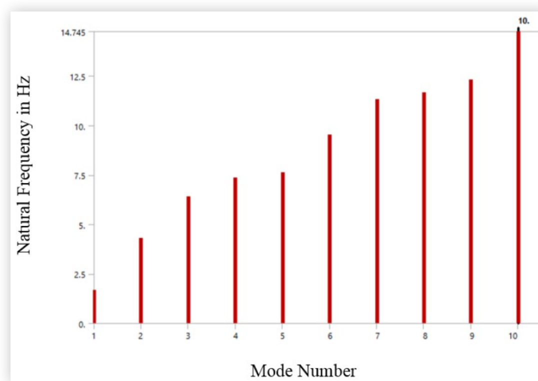

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FIGURE 10 Random Vibration Test Profile

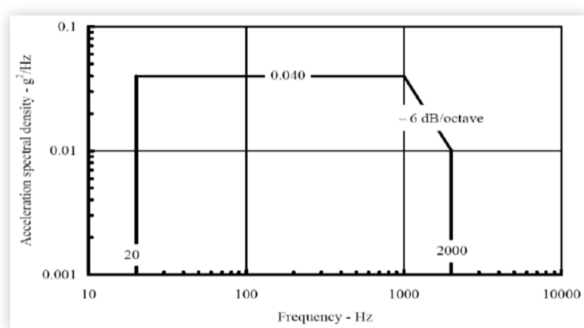

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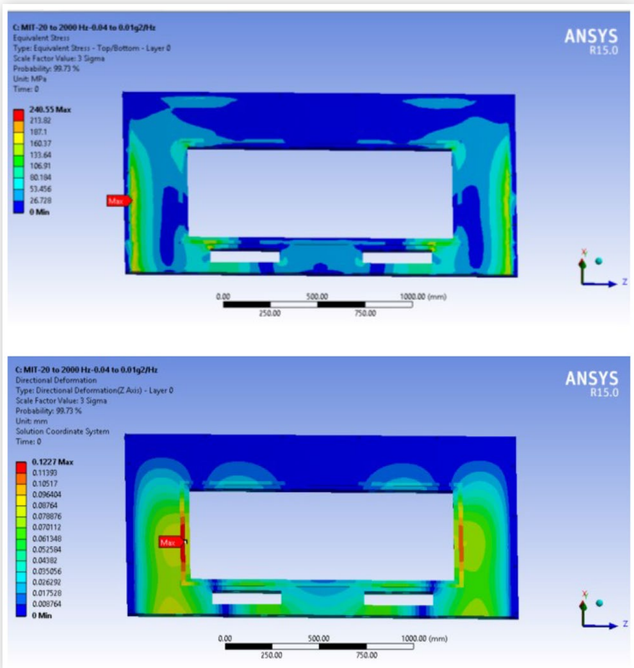
FIGURE 11 Random Vibration Stress & Deformation Results



Shock Response Spectrum (SRS) Analysis

The SRS in addition to vibration is another test to determine the structural integrity of the system or component. In this analysis a high amplitude shock of fixed time duration is applied as per standards. In this case for MBTs a shock of 40 g amplitude with time duration of 15 ms is considered ideal. Similar to MIT, modal analysis results also form one of the inputs to this analysis. With these inputs the response acceleration, stress & deformation are given in Figure 12.

Steady State Thermal Analysis

This analysis is carried out as a part of the design, as the cover plate is located over the powerpack compartment that includes the 1400 hp engine and transmission. As a result, the cover plate bottom portion in this case Kevlar stackup will be subjected to high temperature. During normal day & night conditions the compartment temperature is well below 90°C, whereas during peak summer the temperature observed is 110°C. This worst-case scenario is used as an input to carry out the steady state thermal analysis to determine the thermal efficacy of the design. The total heat flux observed during this analysis is given in Figure 13.

Penetration Analysis

This analysis is basically an explicit dynamics study in which, a penetrator of known dimensions with a given velocity is made to strike a target to know its capability to withstand ballistic attack. In this case, the penetrator used is a 7.62 mm x 39 API bullet against which the composite panel with a given level of protection (Level-II) is to be designed [15]. This bullet modeled as per known dimensions [16], is set against the target with a strike velocity of 690 m/s. This input is in addition to the material models already discussed. For this analysis, a composite panel of 300 x 300 mm is used instead of the full

FIGURE 12 SRS Directional Acceleration, Stress & Deformation Results

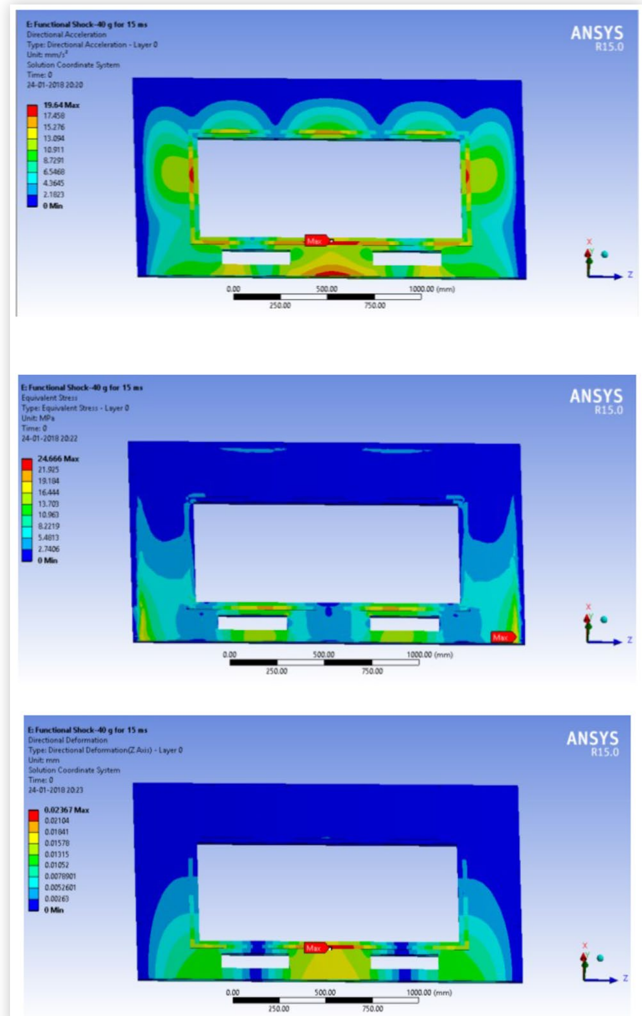


FIGURE 13 Total heat flux distribution

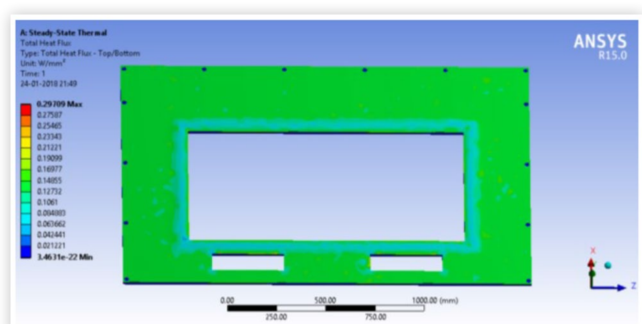
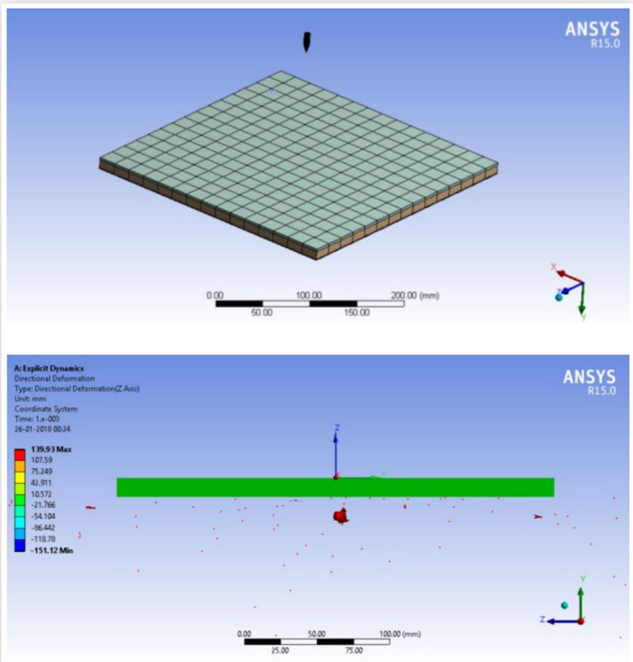


FIGURE 14 Meshed explicit model & Deformation Results



composite cover plate to save unnecessary computation time. The model and deformation results are shown in Figure 14.

Results & Discussion

The different analysis carried out to validate the composite cover plate design and their results are detailed above. To analyse and infer the results better, the stress, deformation, acceleration, heat flux etc., are tabulated as shown in Table 4.

A cursory at the static structural results reveal that the Von-Mises stress and deformation are well below the acceptable values for the cover plate. Similarly, the modal frequency values (all ten modes) are less than 20 Hz, thus indicating that the composite cover plate may not resonate as it does

TABLE 4 Summarised Results for composite cover plate

Analysis	Results
Static Structural	Equivalent Stress: 19.576 MPa Deformation: 1.146 mm
Modal	First Mode: 1.674 Hz Tenth mode: 14.745 Hz
Random Vibration	Equivalent Stress: 240.55 MPa Directional Deformation: 0.122 mm (Z axis)
SRS	Directional Accl: 19.64 mm/s^2 Equivalent Stress: 24.666 MPa Deformation: 0.236 mm
Steady State Thermal Analysis	Total Heat Flux: 0.297 W/mm^2
Penetration	Deformation:0 mm on target plate

FIGURE 15 Fabricated composite cover plate for MBT

not fall between 20 to 2000 Hz. However, the random vibration stress value of 240.55 MPa is although above the yield value of 210 MPa for SS, failure is unlikely to happen as it occurs on the ceramic tile. Since, this stress is compressive in nature and as the ceramic tile has an ultimate strength of 2000 MPa this is unlikely to cause failure or affect the design.

Regarding the SRS analysis, it is observed that out of an input acceleration amplitude of 40 g, only 0.0019 g is likely to be transmitted, thus indicating the damping efficacy of the cover plate. In addition, the total heat flux is also well below the limit values and hence acceptable. Also, the 7.62 mm x 39 penetrator does not cause either penetration or perforation, thus validating the design of the composite cover plate. Finally, by adopting the above design methodology it is observed that the weight of the composite cover plate is 140.66 kg whereas a monolithic rolled homogenous armour plate made cover plate weights around 220 kg which leads to a weight saving of 75-80 kg.

Prior to fabrication, as a proof of concept a ballistic panel of predefined size is fabricated and subjected to ballistic testing as per NATO STANAG 4569 & AEP-55 standard using Level-II Projectile or bullet. This projectile fired with a terminal velocity of 690 m/s should not cause any cracks, penetration or perforation. As expected the fabricated panel did not cause any of these failure modes thus proving that the design is robust and fit for fabrication. Once ballistic resistance is evaluated and proven, the cover plate is fabricated confirming to the design methodology as shown in Figure 15. This cover plate is subjected to limited automotive trials i.e. 100 km on cross country prior to full testing and till date no abnormalities is observed.

Conclusion

The design methodology evolved for designing a cover plate for a MBT made of composite laminate with ceramic tile, SAN Foam, Kevlar and SS top plate is presented. To withstand all the load cases, the approach is to increase stiffness and corresponding mass reduction. To obviate the high safety factors observed in the static structural results, a thickness reduction results in a corresponding increase in modal frequencies within the 20-2000 Hz and panel bulging in explicit analysis which is unacceptable. Although the design cost for this solution is 23% higher than RHA Steel, a weight saving of around 35% is achieved without compromising on functionality or protection which serves the objectives of this investigation. Finally, considering the need to deploy these platforms at high altitude areas using air transport, the weight advantage accrued far outweighs the cost overrun.

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