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DYNAMIC LOADS ON THE ROOF PLATE OF THE WHEELED CARRIER DURING THE FIRING OF A 30 MM CANNON

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Abstract

On the battlefield, modern vehicles perform a variety of roles. Transportation is one of the most fundamental. Operating in different terrains, including urban areas, means exposing the crew to different hazards. To increase crew protection, passive and active protection systems are used. On the other hand, in addition to protection, support of the infantry in offensive operations is an equally important activity. The most common solution for medium wheeled vehicles is a manned turret. The weapon is a 30 mm cannon. Nowadays, there is a trend towards installing systems that allow such weapons to be operated remotely. This minimises the exposure of highly trained personnel. This paper presents the results of a numerical study of the dynamic loads on the roof-plate structure of a wheeled armoured personnel carrier resulting from the firing of the vehicle's main armament. It includes the values of the strains and stresses in the upper plate structure and the forces transmitted by the brackets connecting the roof plate to the bottom plate, and an assessment of the risk of using such a system on the safety of the vehicle structure and its crew.

Keywords: finite element method; armoured personnel carrier; shock loads; structure stresses

1. Introduction

The effectiveness of military tasks performed by multi-axle armoured vehicles depends on the acceptance of the expected operating conditions at the design stage. In general, this means establishing appropriate tactical, technical and design requirements. It is also necessary to establish limits for relevant parameters describing characteristics such as the firepower of the basic armament, the ability to protect personnel and internal equipment, and the ability to operate in different road conditions. These characteristics are also shaped by the expected range of operations. An important factor influencing the geometry and overall design of the vehicle is the weapon system – including the mass, calibre and recoil force of the cannon. The design is intended to be modular. This approach provides a well-prepared support structure (e.g. self-supporting body and hull) capable of accommodating special

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equipment that generates shock loads of varying intensity. An important structural node in this case is the connection between the roof hull plate and the turret system. In the horizontal plane, armament systems for this class of vehicle can generate loads over the full angular range. These vehicles must be as light and small as possible. This means that specific hull structures have to be designed for each armament system. The focus on universality of the hull structure on the one hand, and weight minimisation on the other, thus creates additional requirements that may conflict with each other [32]. For this reason, the design of special hulls is not a matter of optimisation, but rather a matter of compromise. Therefore, before any decision is taken on changing the purpose or equipment of an armoured vehicle, the necessary tests have to be carried out.

A numerical approach to the design and development of new structures is a common practice used by R&D facilities. There are two common approaches. One is based on rigid body modelling and the other is based on the finite element method (FEM). For example, a six-degrees-of-freedom model is used to model a four-wheeled vehicle with a mounted mortar in [8]. Weapon firing effects (including impact amplitude, duration, and elevation angle) are investigated. However, FEM analysis offers much broader possibilities. These include modal analysis and evaluation of the structural response to static and dynamic loads. The results of tests conducted to determine the exposure of crew and special equipment to hazards such as direct fire, shrapnel, anti-tank mine blast or improvised explosive device have been presented in [22, 33]. This approach allows to develop solutions offering improved protection [24, 27, 28] and parametric optimisation [34] to minimise crew exposure as much as possible. Compliance with international requirements, such as NATO STANAG 4569, is another important aspect to consider in the design process.

Numerical methods have a wide range of applications, such as the simulation of the effects of different armour and protection configurations on crew protection levels, internal equipment, traction and operational characteristics. The advantage of this method, when combined with relevant data and compared to real object testing, is a significant reduction in cost, identification of sensitive structural nodes, and determination of resonant frequencies. All of which can have a significant impact on the durability and reliability of specialised equipment, as well as the accuracy of weapons [4]. However, to ensure that the results obtained are reliable, the numerical model needs to be validated. A number of different approaches have been presented in the literature for this purpose. One possibility is to validate the individual assemblies that form part of the overall test object. An example of this approach for wheel carrier suspension components is presented in [12]. The most reliable method is to carry out a full-scale experimental study on a real object. Unfortunately, such tests are expensive and, in the case of armoured vehicles, can result in destroying the tested object. Research using dummy models or isolated parts of the structure is an alternative approach. However, predicting the behaviour of the vehicle as a whole is not always possible.

An important step in the solution process is the validity of the finite element model for a specific structure. Experimental modal analysis correlates with the FEA model by evaluating the structural dynamics. The parameters used to correlate the finite element model are the modal properties (such as natural frequencies and mode shapes) [6, 15].

Modal analysis provides valuable information about the dynamic properties of engineering objects. This technique is used in many technological fields and validates the numerical model. The hull of a combat vehicle, including the fragments of its protective structures, has previously been analysed using this approach [9, 25]. Results of experimental and numerical modal analysis of the bottom plate of an armoured personnel carrier hull are presented in study [13]. Both the standard mode indicator function approach and the modal assurance criterion approach were used to determine the frequency and mode shape of the natural modes for comparison. The authors' method of comparing mode shapes using an interpolation function was also presented. The structure was excited using an impact hammer. This method allows the study of structures with both small and large dimensions, regardless of the construction materials. Results for modal studies of composite plates, together with possible applications for validation using numerical models, have been presented in other literature reports [29]. A special approach to the determination of dynamic properties should be taken for very large and complex structures. Due to the lack of possible external excitation, the natural vibration generation of the working device was used for the analysis. An example of this type of approach has been presented in the literature [31] for a surface mining machine, where an experimental application was used for the determination of the modal characteristics and subsequently for the upgrading of the working elements. Similar considerations have also been presented in other works [30]. Experimental results have been compared with numerical results.

There are papers in the literature that point to a significant influence of vibrations of weapon system structural components on firing accuracy [4, 5, 16]. However, the results presented are limited to barrel vibrations. In [4], examples of considerations related to the vibrations of a tank cannon were presented. In [16], the influence of the barrel vibrations of a 120 mm cannon on the projectile behaviour was investigated. An experimental numerical analysis of the barrel vibrations of a machine gun during active firing has also been the subject of investigation. Pressure changes within the barrel and their effect on the dynamic loading of the weapon structure have also been taken into account. The method of weapon mounting becomes extremely important in weapon systems characterised by high rates of fire. The high frequency recoil force generated can cause structural vibrations that reduce accuracy. For a machine gun mounted on a tripod base, the problems of vibration reduction and improved firing accuracy have been discussed in the literature [14]. The strong influence of the vibration frequency of the gun's self-supporting structure on the firing accuracy was demonstrated, as well as optimisation possibilities for the dynamic structure properties. The accuracy of the fire is also strongly influenced by the quality of the weapon stabilisation systems, but also by the characteristics of the vehicle suspension, including its spring and damping components, as well as the influence of the technical and environmental conditions [11, 12].

The aim of this study is to assess the risk of using a 30 mm calibre cannon armament on the operational safety of the transporter structure and its crew. In order to achieve this objective, the stresses and strains of the roof plate structure and the axial forces transmitted through the brackets connecting the roof plate to the bottom plate during the firing of the main armament are evaluated. The turret with the cannon is mounted on the roof hull plate of the APC through a bearing that allows firing in any direction (360 degree rotation). The effect on the loads on the structure of a single shot to the front, to the left and to the rear for a cannon elevation angle of 0° was analysed. The aim of this study is to assess the hazards of using medium-weight wheeled armoured personnel carrier during firing, in particular for the carrier hull structure, which is based on a numerical model of a validated hull FEM model.

2. Object of research

The wheeled armoured personnel carrier has eight-wheel drive (8x8). A 30 mm turret-mounted cannon is the main armament. It has independent hydro-pneumatic suspension. The wheels are guided by double wishbones. The self-supporting hull is made of welded steel plates forming a flat-bottomed hull. The transporter hull is connected to the frame, to which the wheel suspension, drive and steering components are attached. Run-flat inserts are used in the wheel rims. The vehicle is equipped with a central wheel pumping system. The crew consists of three soldiers (commander, driver, gunner). The landing compartment can carry 6–8 landing troops, depending on the version. It is possible to install additional external armour to enhance the protection level of the crew.

2.1. Numerical model

The numerical model of the hull was built with more than 150,000 shell elements. The average edge length of the element is approximately 20 mm. In addition to the hull plates themselves, the model takes into account the presence of structural reinforcements, installation brackets and structural and technological holes. These elements have a significant effect on the stiffness of the structure and therefore on its vibration. The entire structure is loaded with earth acceleration. One-sided constraints are also defined.

The hull of the vehicle is made of ARMOX 500T armour plate. The elastic-plastic material model with isotropic hardening including a strain rate effect was used to describe the properties of the steel elements (material data are given in Table 1). The choice of constitutive model for the material was dictated by the intended scope of the model tests, including the APC impact loading, which involved calculations of the strains and stresses on the structure caused by a rapidly changing load resulting from the recoil force of the cannon or the effect of a shock wave.

The Johnson-Cook model provides a satisfactory prediction of yield stress for large strains and high strain rates when the dependence on strain rate is linear on a semi-logarithmic scale. For modelling problems related to crash testing or the effects of explosive charges, this model is commonly used [1, 23]. The mathematical formula describing this model is as follows [7, 17]:

$$\sigma(\varepsilon,\dot{\varepsilon}) = (A + B \cdot \varepsilon^n) \cdot \left(1 + C \cdot ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right) \tag{1}$$

where A is the yield stress of the material under reference conditions, B is the strain hardening constant, n is the strain hardening coefficient, C is the coefficient responsible for kinematic strengthening (for strain intensity effects), and ε, $\dot{\varepsilon}$ is the equivalent plastic strain and equivalent plastic strain rate, respectively, and $\dot{\varepsilon}_0$ is the reference strain rate.

The mechanical properties and material data for Armox 500T taken from the results of experimental studies presented in [26] are shown in Table 1. The parameter values were not changed in the numerical tests.

Tab. 1. Mechanical Properties and Material Data for Armox 500T [26]

$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]	Hardness HBW	Elastic Modulus E [GPa]
1250 (minimum)	1450–1750	8 (minimum)	480–540	207
A [MPa]	**B [MPa]**	**n**	**C**	**m**
849	1340	0.0923	0.00541	0.870

LS-Dyna software was used to model the hull structure. An important unit is the turret bearing. It allows the turret to rotate and is responsible for transferring forces between the hull and the transporter turret. Omitting it from the model significantly alters the response of the structure to the applied loads. Preliminary investigations showed that the introduction of rigid connections between the turret and the hull (e.g. at the locations of the rollers) did not allow the plot courses recorded in the experimental studies to be obtained.

In the literature it is possible to find proposals for different solutions to the problem of bearing modelling. They are largely related to load tests at the point of contact between the rolling elements and the rails [2, 36] or tests of resistance to motion [19]. Solid elements are usually used to develop the model, while flexible models are used to describe the material properties. Bearings were considered as a direct object of interest in the referenced publications. They were not part of a more complex load bearing rotating structure. For applications where the bearing is one of many components, certain simplifications are usually made. The authors used simplified models of the bearing balls in the papers [3, 18, 20] and [21, 35]. They chose to use the truss element and a spring with non-linear characteristics.

In the case of the object under consideration, modelling a complete bearing with rollers would be complicated and increase the calculation time. The bearing rails were modelled using solid elements, while the rolling elements were represented by elastic damping elements with non-linear characteristics. This ensured that the elasticity of the entire bearing was taken into account, as well as the internal clearance.

The paper [10] presents the results of experimental and numerical studies. The experimental studies included modal analysis of the hull roof plate and impact loading of the structure. As part of the study, the frequencies and natural modes of the hull roof plate were determined. The results of the experimental tests were compared with the results of the numerical research (a generalised eigenvalue problem was solved). The hull model has been positively validated for natural frequencies, mode shapes and dynamic response to shock loading.

The hull model has been extended to include elements such as additional armour, an integrated intermediate mount, double wheel guide arms, spring-damper suspension components and a source of shock loads – the turret fitted with a 30 mm calibre cannon. The spring and damping elements of the suspension were modelled as discrete elements. The tyres were modelled as solid elements on the wheel hubs. They are intended to reflect the radial properties of the tyre. A contact (rigid wall) was defined between each wheel and the rigid surface. This allowed the one-sided constraint and friction between the ground and the tyre to be included. The model consists of 470,000 shell elements, 35,000 solid elements and 16 discrete elements. The view of the complete vehicle with turret system is shown in Figure 1.

Fig. 1. Wheeled armoured personnel carrier: a) isometric view, b) view from left side

2.2. Methodology

Model tests were carried out on a vehicle with a turret fitted with a 30 mm calibre cannon. A force impulse of 35 kN and duration of 20 ms was applied to the hinges of the cannon (Figure 2a). The tests were carried out for three variants of turret and cannon rotation. The reference variant is the turret with the cannon positioned for forward firing. In Figure 2b a dashed line marks the position for forward firing ($\varphi = 0°$). Tests were also performed for a shot to the left of the hull (turret with gun rotated by $\varphi = 90°$) and a rearward shot (turret with cannon rotated by 180°). For each angle of turret rotation, the elevation angle of the cannon was 0°. The calculations were performed using LS-Dyna software (revision 12 MPP double precision solver).

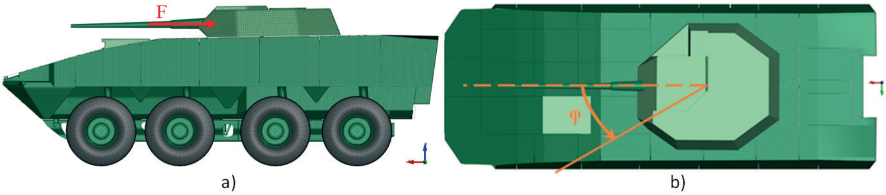

Fig. 2. Wheeled APC with turret and 30 mm cannon; (a) recoil force applied to cannon hinges, (b) turret rotation angle with cannon

The strains and stresses of the hull roof plate structure were assessed in the three areas indicated in Figure 3a. The first (area I) on the outer surface of the slab stiffening profile. The second (area II) on the inner surface of the plate in the area between the bearing and the left bracket flange, while the third (area III) on the inner surface of the plate in the area between the bearing and the right bracket flange. The values of reduced stresses according to the Huber-Mises hypothesis were also determined for the same areas. The axial forces transmitted by the brackets connecting the top plate to the bottom plate were also determined. A view of the flanges with the brackets is shown in Figure 3b (green colour).

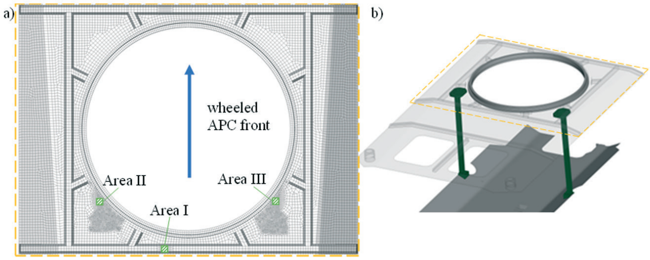

Fig. 3. Locations of; (a) strain and stress evaluation in areas I, II, III, (b) location of brackets

3. Results

Figure 4 shows the time diagrams of the strain of the structure in areas I, II, III for three positions (rotations) of the turret: a) with the gun facing forward, b) with the cannon facing left, c) with the cannon pointing rearward. In each of the variants considered, the elevation angle of the cannon was 0°.

In the case of a forward shot, the highest deformation occurred in area I, reaching a value of 84 μm/m. The shot with the gun pointing to the left resulted in an increased maximum strain value. As before, it occurred in area I and reached a value of 137 μm/m. The highest strain value was observed for the turret with the cannon pointing rearwards. Once again, the highest values occurred in Area I and reached a value of 514 μm/m. The data for the other areas are summarised in Table 2.

Areas I–III were also evaluated for reduced stress values (according to the Huber–Mises hypothesis). For a single forward shot, the highest stress values occurred in area II and reached a value of 53.4 MPa. For a shot to the left, similar to the above, the highest stress value was 52.7 MPa in area II. The highest value of reduced stress was observed for the single shot to the rear, where the highest reduced stress occurred in area I, reaching a value of 81.2 MPa. Table 2 summarises the values for all variants.

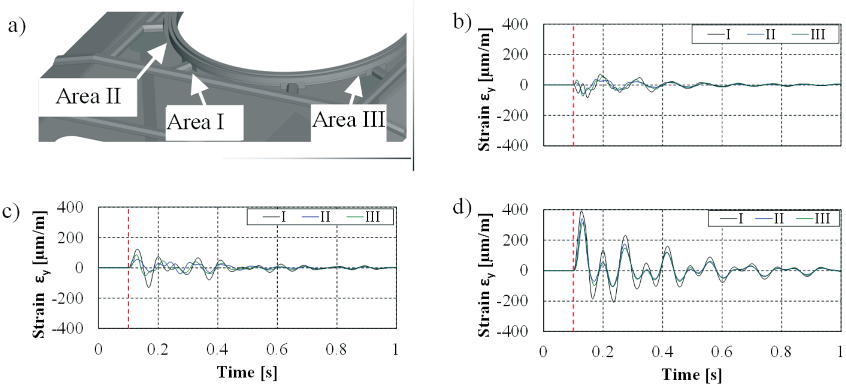

Fig. 4. Strain in areas I, II, II caused by; (a) firing forward, (b) firing left, (c) firing rearward

Reduced stress (von Mises) maps generated for a common colour scale are shown in Figure 5. The grey colour indicates the areas of the structure where the stress values do not exceed 50 MPa, while the red colour indicates the areas of the structure where the values reach stress values of more than 500 MPa. In the case of forward firing (Figure 5a), a stress concentration was observed in the area of the roof plate between the bearing and the left bracket flange. The reduced stresses in this area reach 100 MPa. For the turret with the cannon pointing to the left (Figure 5b), the level of reduced stresses is 130 MPa. The highest level of reduced stress occurred when the turret gun was facing the rear of the hull (Figure 5c). In this case, the reduced stresses reached a level of 150 MPa.

Tab. 2. Strains and stresses in evaluated areas

Angle of rotation [°]	Area I		Area II		Area III	
	Strain [μm/m]	Stress [MPa]	Strain [μm/m]	Stress [MPa]	Strain [μm/m]	Stress [MPa]
0	84.1	20.7	58.8	53.4	72.7	26.1
90	137	35.9	66.7	52.7	108	27
180	514	81.2	409	59.8	363	52.1

Figure 6 shows the forces transmitted through the roof plate connecting the bottom plate for three turret positions: a) with the cannon facing forward, b) with the cannon facing left, c) with the cannon facing rear. The angle of elevation of the cannon was set to 0° in each case. When the cannon was firing to the front, the right bracket transmitted approximately twice as much axial force as the left bracket, reaching a value of 14 kN. The opposite occurred when the cannon was aimed to the left.

The left bracket transmitted almost three times the axial force of the right bracket, reaching a value of 17.2 kN. The highest values of axial forces occurred for the rear-facing cannon, exceeding the value of 25 kN. The value of force transmitted by the left bracket was 4.6 kN higher. The individual values for all variants are summarised in Table 3.

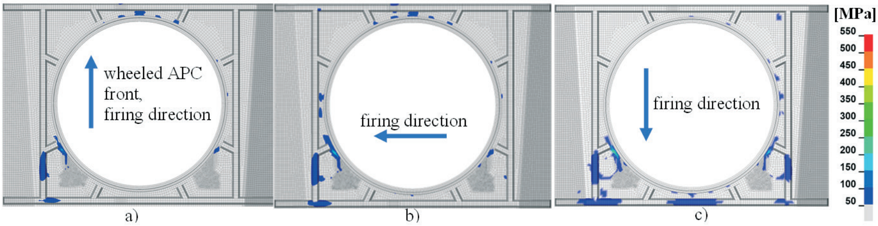

Fig. 5. Reduced stress maps according to the Huber-Mises hypothesis caused by; (a) firing forward, (b) firing left, (c) firing rearward

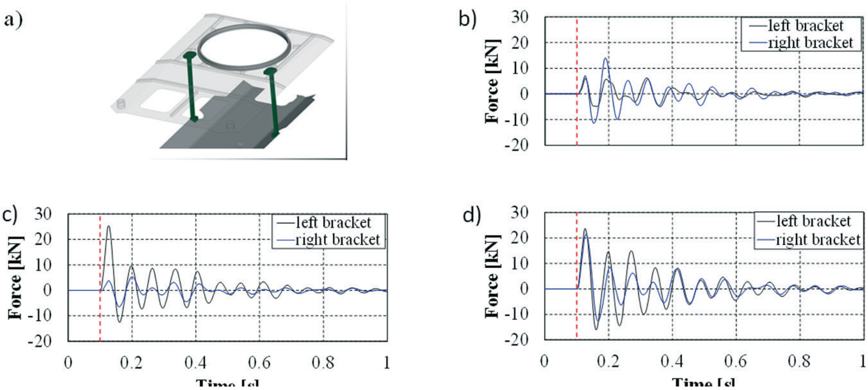

Fig. 6. Forces transmitted by brackets; (a) location of brackets, (b) cannon firing forward, (c) cannon firing to the left, (d) cannon firing rearwards

Tab. 3. Axial forces transmitted by brackets

Angle of rotation [deg]	Force [kN]	
	Left bracket	Right bracket
0	6.4	14
90	17.2	6.6
180	29.7	25.1

4. Conclusions

The analysis of the results of the numerical study of the loads acting on the structure of the hull roof plate of a wheeled armoured personnel carrier with a weapon system installed in the form of a turret with a 30 mm calibre cannon for an elevation angle of 0° allows to conclude that:

- due to the asymmetric design of the hull, the left side is more heavily loaded;
- regardless of the direction of fire, the greatest deformation of the structure occurred on the outer surface of the profile located behind the turret bearing (area I);
- regardless of the firing direction, the highest value of reduced stress occurred in the area of the hull roof plate between the bearing and the flange of the left bracket connecting the bottom plate to the top plate;
- the highest stress values in all considered areas of the hull roof plate structure occurred for the rearward shot;
- the highest value of axial forces transmitted by the brackets occurred in the rearward shot;
- the highest stress on the plate occurred in the area to the left of the bearing, reaching values of 150 MPa;
- achieved levels of plate strain do not pose a threat to the safe use of the weapon system.

The numerical model developed can also be used to assess the loads acting on a transporter equipped with a large-calibre cannon, as well as other weapon systems, e.g. mortars or anti-aircraft guns.

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6. Nomenclature

APC	Armoured Personnel Carrier
FEM	Finite Element Method
NATO	North Atlantic Treaty Organization
STANAG	Standardization Agreement Document

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