MODELLING AND NUMERICAL SIMULATION OF THE PROTECTIVE SHIELD – PROTECTED PLATE – TEST STAND SYSTEM UNDER BLAST SHOCK WAVE

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Abstract

The study presents FE modelling and simulation of a system for range testing of protective shields for light armoured vehicles. The protective shield designed by Authors is used against HE mines and IEDs up to 10 kg TNT. The system consists of the multiple-use portable range stand, a protected Armox 500T steel plate and a protective shield. The shield has a multi-layer structure and has the following main layers: PA11 aluminum, SCACS hybrid laminate, ALPORAS aluminum foam, SCACS hybrid laminate, connected together using SOUDASEAL chemo-set glue. The HE spherical charge is suspended centrally at 400 mm distance from the top surface of the stand. Overall dimensions of the test stand are approximately 800×800×180 mm, the protected plate has dimensions 650×650×5 mm, and the protective shield is of 450×450×76 mm dimensions. The system is supported by an additional steel plate stiffening the subsoil. FE modelling, numerical simulations and processing the results were performed for the system under blast shock wave using the following CAE systems: CATIA, HyperMesh, LS-Dyna, and LS-PrePost. The 8-nodes brick finite elements were used, taking into account friction and contact phenomena. Isotropic and orthotropic material models and advanced nonlinear equations-of-state for some parts of the system were chosen, with relevant failure and erosion criteria, including the Johnson – Cook model for Armox 500T steel and PA11 aluminum and the MAT_161 model for plies of hybrid laminates. The shock wave was modelled approximately using the LOAD_BLAST_ENHANCED option available in LS-Dyna Version 971 R4 Beta code. Numerical simulations were performed for 2 kg TNT.

Keywords: *light armoured vehicle**,** protective shield, aluminium – hybrid laminate – foam shield, blast shock wave, modelling and simulation*

1. Introduction

The study develops FE modelling and simulation of the system for range testing [13] of various protective shields for lightly armoured vehicle bottoms. The protective shield has been designed by Authors as adequate against HE mines and IEDs up to 10 kg TNT [14]. The study is focussed on developing a methodology for FE modelling and simulation of the system loaded by the blast shock wave, suitable in engineering practice. Preliminary simulations of the numerical model of the system, corresponding to the protected plate without and with the protective shield under 2 kg TNT blast explosions, are presented in the study. Respective range experiments used for validation of the FE models are described in Ref. [9].

Fundamentals of blast waves are presented e.g. in Ref. [18]. Explosives during detonation produce violent exothermal chemical reactions resulting in mechanical work through the evolution of highly compressed hot gases. The surrounding medium generates a pressure jump reaching values of tens GPa. The shock wave propagates within the range 10^3-10^4 m/s.

Recent research related with the blast loading is mainly aimed on developing new concepts of protective panels for various structures and military vehicles [3, 5, 6, 17]. The panels are usually designed and manufactured as removable and made from different types of energy-absorbing materials, such as polymer-matrix composites, ceramics, elastomers, or metal foams. Such materials are characterized by high relative energy-absorption capacity. Writers of Ref. [2] present FE modelling and simulation of blast wave/pipeline interaction. The pipe has been equipped with composite – foam cylindrical protectors. The MSC.Dytran code and the ALE description were used for simulations in reference to 1m long fragment of the pipe.

Recent research investigations also concern sandwich protective shields, designed for structures and vehicles, with a core composed of tubular or conical thin-walled elements, e.g. [2, 7, 10, 12]. A review of up-to-date protective shields against HE mines and IEDs presents Barnat [1]. A protective shield designed in this study differs from other solutions described in Ref. [1] and in patent applications [15, 16].

2. Description of the SPS system

The SPS system consists of the multiple-use portable range stand [13], a protected Armox 500T plate and a protective shield. The full description of the range stand is presented in Ref. [9]. The range stand for testing protective shields against blast loadings is composed of three closed steel frames, respectively graded and connected together with high strength M20 erection bolts. The total weight of the stand amounts to 326 kg. The stand has been designed to be resistant against HE blasts and IEDs up to 10 kg TNT charges. The tested object is a square plate of 650×650×5 mm dimensions, made of Armox 500T steel. The plate is located inside the test stand between the top and the intermediate frames with vertical and horizontal clearances equal to 2 mm and 10 mm, respectively. Thus, the plate can slide with friction in the 100 mm wide edge zones. It results in possibility to select plastic deformations of the protective shield and the protected plate.

The design requirements put on the protective shield are as follows:

1) the shield is to protect a light armoured vehicle bottom against HE mines and IEDs up to the III level according to STANAG 4569 standard [8],
2) a thickness of the shield cannot exceed 78 mm,
3) a surface mass density of the shield cannot exceed 55 kg/m^2.

Based on preliminary design calculations, ballistic tests and numerical simulations, Authors have designed the aluminium – hybrid laminate – foam shield, denoted with ALF code, of 76 mm thickness and 50 kg/m^2 surface mass density. The shield consists of the following main layers [14]: EN AW-5754 (PA11) aluminum sheet, SCACS hybrid laminate, ALPORAS aluminum foam, and SCACS hybrid laminate. The main layers are connected together using SOUDASEAL chemo-set glue in the form of additional layers. At the preliminary range tests stage, the shield is connected to the protected plate with the glue layer as well. The SCACS hybrid laminate plates, manufactured using the vacuum technology, are 28-ply composites with the specified sequence of GFRP, CFRP and KFRP laminates with incombustible VE 11-M vinylester resin matrix [14]. The following woven fabrics have been used: S SWR 800 glass fabric, Style 430 / Carbon 6K carbon fabric, and Style 328 / Kevlar 49 T 968 / T 968 TG aramid fabric.

Overall dimensions of the test stand are approximately 800×800×180 mm, the protected plate has dimensions 650x650x5 mm, and the protective shield is of 450×450×76 mm dimensions. The system is supported by an additional St3 steel plate with a square hole, stiffening the subsoil.

The HE spherical charge is suspended centrally at 400 mm distance from the top surface of the stand. The simulations have been performed for 5 mm thick protected plates made of Armox 500T steel.

3. FE modelling and simulation of the PS and SPS systems and analysis of the results

The FE model was developed with CATIA and Altair HyperMesh software. LS-PrePost programme was used as a pre-processor for defining all necessary parameters such as boundary conditions, element properties, material properties, a solution type. Complete FE model was exported as a key file with LS-Dyna preferences. The Lagrangian domain was limited by two planes of symmetry of the SPS system to reduce CPU time. For all simulations the LS-Dyna nonlinear explicit code was used.

The 8-nodes brick finite elements with one integration point were used, taking into account contact and friction phenomena. The FE model of the protected plate – range stand (PS) system has about 98,000 DOFs, whereas the FE model of the protective shield – protected plate – range stand (SPS) system has about 282,000 DOFs. The FE models are relatively dense and finite elements' dimensions satisfy the aspect ratio condition before and during the blast loading.

The exact simulation of the blast/structure interaction using LS-Dyna v971 code requires the use of the burn model described by the velocity of the detonation wave and the thermodynamical parameters on the detonation wave front. In this study, the shock wave was modelled approximately using the LOAD_BLAST_ENHANCED option offered by LS-Dyna system [4]. This load model defines an airblast function for the application of pressure loads due to the explosion of conventional charge, including enhancements for treating reflected waves, moving warheads and multiple blast sources. A type of blast source is spherical free-air burst (BLAST=2).

The Automatic_Single_Surface steel – steel contact model has been assumed with the static and kinematic friction coefficients equal to 0.10 and 0.05, respectively. In order to minimize penetrations, the Segment_Based_Contact (SOFT 2) has been selected. The steel – subsoil contact is taken into account with the kinematic friction coefficient equal to 0.20. The initial displacement and stress state resulting from the gravity has been simulated using DYNAMIC_RELAXATION card.

Material models for subsequent parts of the SPS system have been assumed taking into account both Authors' expert knowledge and literature suggestions. In the materials' description original notation of input data assumed in Ref. [4] as well as a system of units used in the numerical modelling and simulation (kg, mm, msec, K, GPa, kN) have been saved.

Armox 500T steel and PA11 aluminum [4]

LS-Dyna material type 15: MAT_JOHNSON_COOK,
Equation-of-state: EOS_GRUNEISEN

This is the Johnson/Cook strain and temperature sensitive plasticity material, used for problems where strain rates vary over a large range and adiabatic temperature increases due to plastic heating cause material softening. The model requires equation-of-state. Material data have been taken from Ref. [11] and others publications.

St3 steel, 10.9 bolt steel and hardened range subsoil [4]

LS-Dyna material type 24: MAT_PIECEWISE_LINEAR_PLASTICITY

This is an elasto-plastic material with an arbitrary stress vs. strain curve and arbitrary strain rate dependency. St3 steel has been used for manufacturing the range stand and the bottom plate that stiffens the subsoil. The 10.9 steel is used to manufacture M20 erection bolts. Material data are taken from well-known references.

Woven fabric composites [4]

LS-Dyna material type 161: MAT_COMPOSITE_MSC

This model is used to reflect the progressive failure criteria, including delamination, in composites consisting woven fabric layers. The failure criteria have been established by adopting the methodology developed by Hashin. The ply sequence type is $[(0/90)_{WF}]_n$. In-plane principal directions are denoted as A, B, whereas out-of-plane principal direction is C. Material data are based on standard experiments performed by Author's.

ALPORAS aluminium foam [4]

LS-Dyna material type 26: MAT_HONEYCOMB

This material model is useful for honeycomb and foam materials. Nonlinear elasto-plastic behaviour can be defined separately for all normal and shear stresses considered to be fully uncoupled. After homogenization, ALPORAS foam is modelled as an orthotropic material. The elastic moduli vary, from the initial values to the fully compacted values. Material data are based on the material card and on the experiments executed by Authors.

SOUDASEAL 2K glue [4]
LS-Dyna material type 27: MAT_MOONEY-RIVLIN_RUBBER
This is a two-parametric material model for rubber. Material data are based the material card and on the experiments performed by Authors.

For each part of the SPS system vibration damping has been taken into consideration via DAMPING_FREQUENCY_RANGE option [4]. This option provides approximately constant damping, i.e. frequency independent, over a chosen range of frequencies. Input data are based on Authors' expert knowledge and LS-Dyna suggestions.

Figure 1 presents the FE numerical model of the SPS system. Numerical simulations were performed for 2 kg TNT explosive charge of spherical shape, suspended centrally over the PS or SPS system at the 400 mm vertical distance from the top surface of the stand. Initiation of the detonation begins in the central point of the HE charge, thus the shock wave front shape is a spherical surface. CPU time for single series amounts to 20 hours for 20 msec real time of the dynamic process.

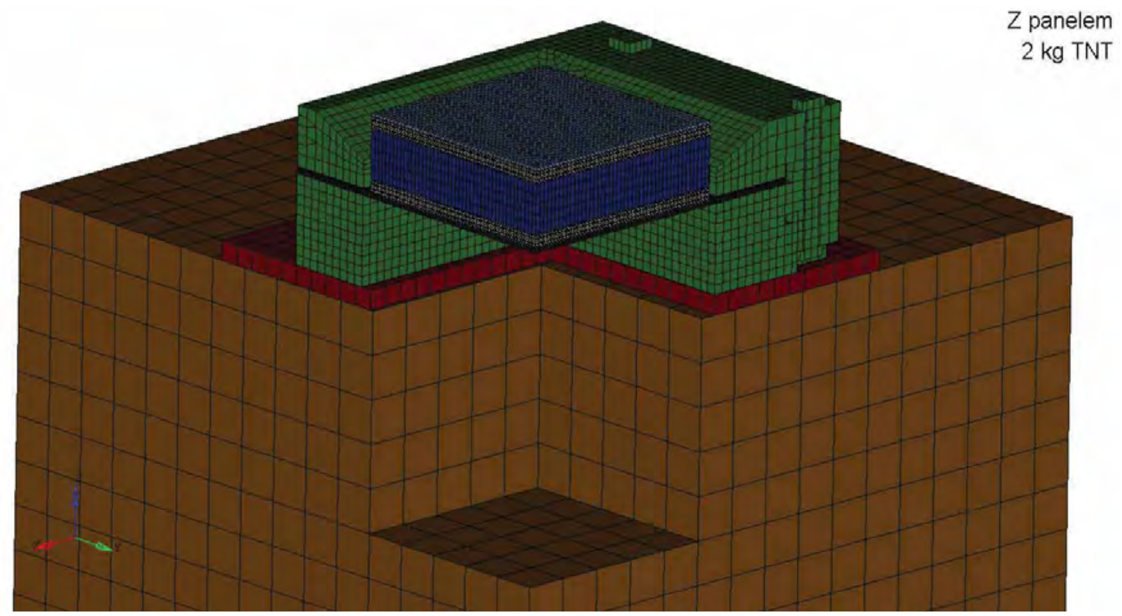

Fig. 1. A quarter of the bisymmetric numerical model of the SPS system resting on the 20 mm thick plate stiffening the subsoil

Representative output results are shown in Fig. 2-6. Vertical deflection time-histories at the midpoint of the protected plate bottom are depicted in Fig. 2. This quantity is understood as the vertical displacement of the midpoint less the vertical displacement of the reference point located in the main cross-section at 235 mm distance from the midpoint. The thin-line curve, corresponding to the PS system, tends to 13.5 mm plastic deflection, while the thick-line curve, related to the SPS system, exhibits only small elastic deflection equal to 1 mm, which probably results from coupling between the excellently protected plate and the seriously damaged protective shield.

Figure 3 presents time-histories of the vertical acceleration at the midpoint of the protected plate for the PS system (thin line) and the SPS system (thick line). Maximum accelerations amount to a(0.16 msec) = 9410 mm/ms^2 in the PS system and to a(4.44 msec) = 3300 mm/ms^2 in the SPS system, thus protection with the energy-absorbing ALF shield results in the maximum acceleration reduced by 2.85 times.

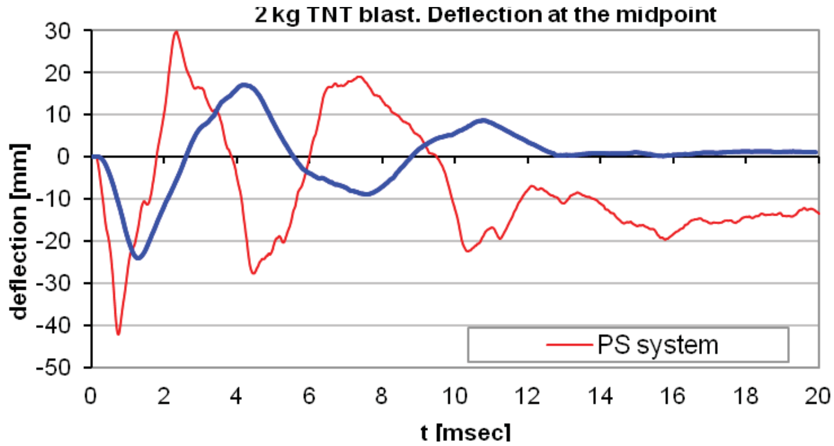

Fig. 2. The vertical deflection vs. time at the midpoint of the protected plate in reference to the PS and SPS systems under 2 kg TNT blast

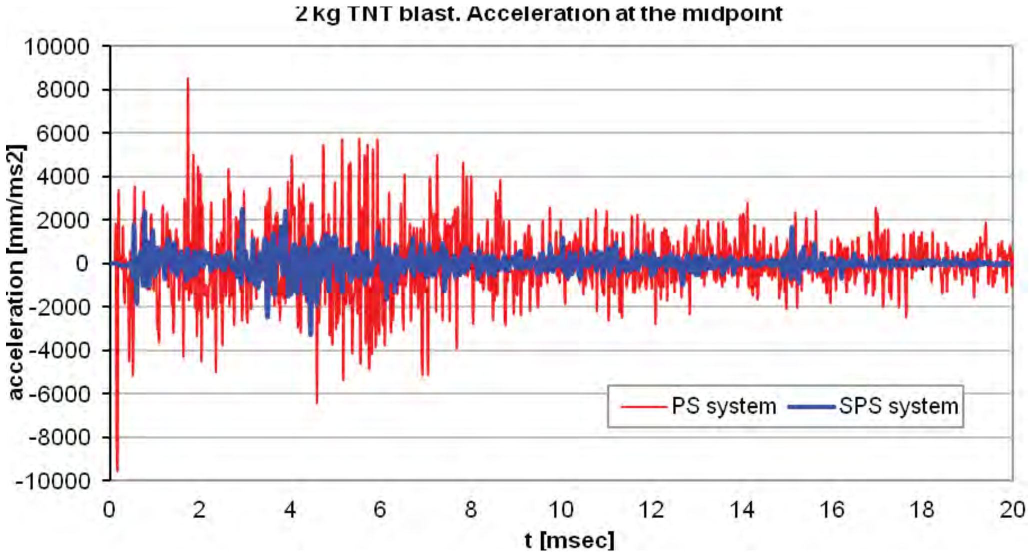

Fig. 3. The vertical acceleration vs. time at the midpoint of the protected plate in reference to the PS and SPS systems under 2 kg TNT blast

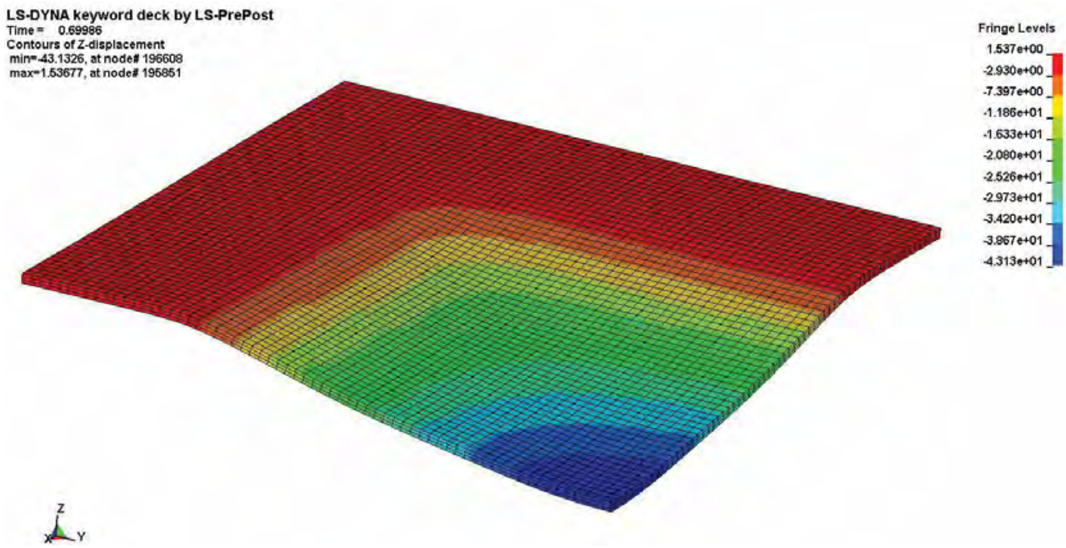

Fig. 4. Contours of the vertical displacements [mm] of the protected plate in the PS system under 2 kg TNT blast, at time 0.70 msec (maximum vertical deflection at the midpoint)

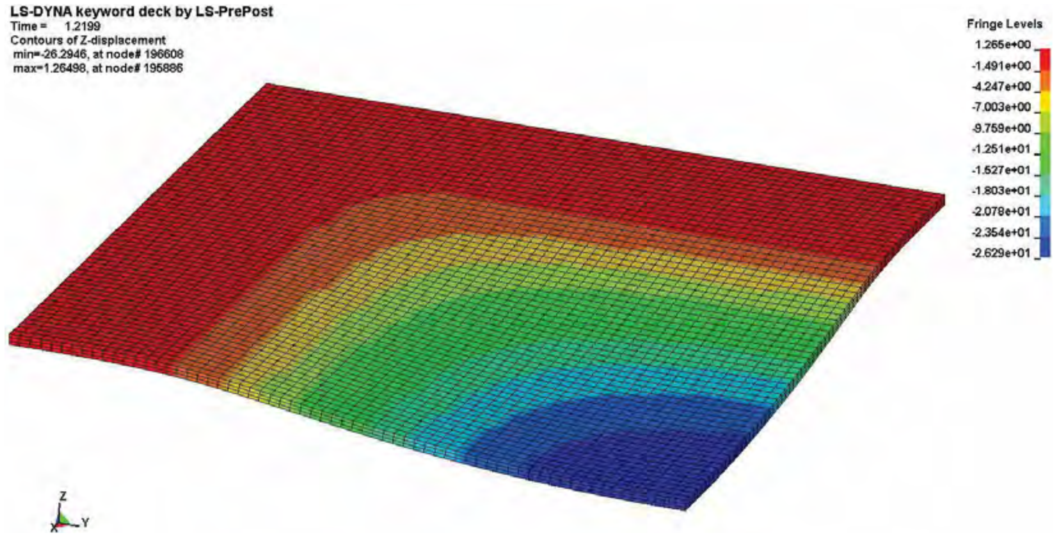

Fig. 5. Contours of the vertical displacements of the protected plate in the SPS system under 2 kg TNT blast, at time 1.22 msec (maximum vertical deflection at the midpoint)

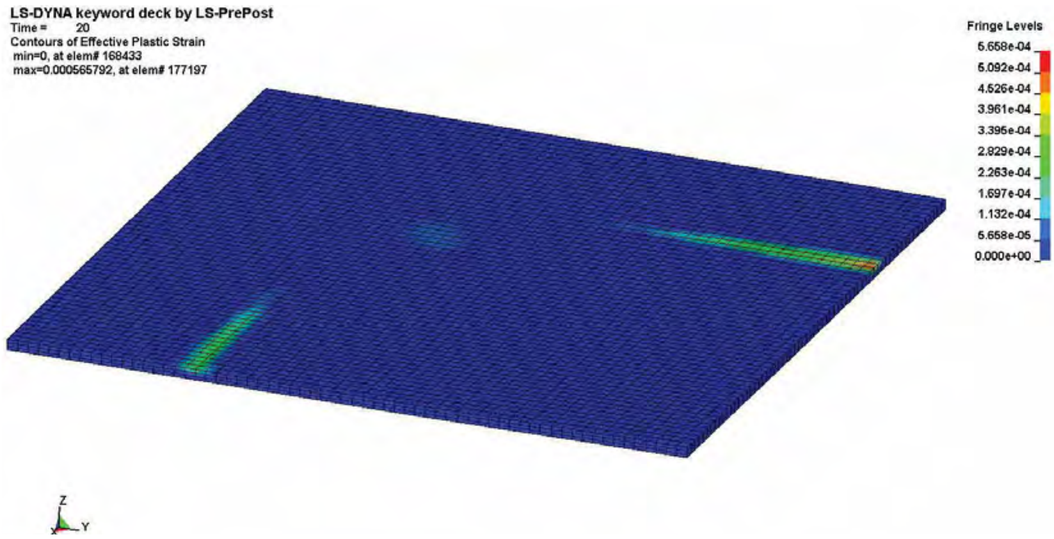

Fig. 6. Contours of the effective plastic strains in the protected plate in the SPS system under 2 kg TNT blast, at time 20 msec (after finishing the dynamic process)

Contours of the vertical displacements [mm] of the protected plate in the PS and SPS systems, at instants when the vertical deflection at the midpoint is maximum, are plotted in Fig. 4 and 5. These figures confirm previous conclusions and constitute the main proof that FE modelling and simulation is correct qualitatively. The range experiments taken by Authors, presented in Ref. [9], validated positively these numerical results quantitatively.

Figure 6 depicts contours of the effective plastic strains in the protected plate in the SPS system, induced by 2 kg TNT blast. Plastic strains in reference to unprotected Armox 500T plate are very large, whereas plastic strains in the Armox 500T plate protected by the ALF protective shield have appeared negligibly small. The latter result is rather from the range stand geometry.

4. Conclusions

The study is focused on developing passive protection of light armoured vehicle bottoms. Based on preliminary simulations and Authors' expert knowledge, a new type of a protective shield has been designed and tested numerically for 2 kg TNT blast shock wave. Moreover, Authors designed a multi-use portable range stand for testing arbitrary protective shields.

The main goal of this study is to develop a methodology of FE modelling and simulation of the SPS system, i.e. the protective shield – protected plate – range stand system, which could be useful in engineering practice. Taking into consideration all possible blast and failure phenomena, Authors selected the most respective finite element type, developed/assumed advanced material models and equations-of-state, and select a large number of respective options in the LS-Dyna system.

Further considerations concerning the ALF protective shield are going to be focused on simulation for larger explosives (6 and 10 kg TNT) and on comparison with respective range tests. Next research could be aimed at optimization of the protective shield from the standpoint of both the blast protection and energy-absorption capability. Next research will be aimed on FSP tests checking resistance against IED. Manufacturing and mounting solutions will be developed as well.

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