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Shock loads induced on metal structures by LHC proton beams: modelling of thermo-mechanical effects

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Abstract. In this work, the numerical simulations of the LHC high energy particle beam impact against a metal structure are performed using the commercial FEM code LS-DYNA. The evaluation of thermal loads on the hit material is performed using a statistical code, called FLUKA, based on the Monte-Carlo method, which returns an energy map on a particular geometry (taking into account all the particles in the cascade generated by the interaction between the proton beam and the target). The FLUKA results are then used as input for thermo-structural studies.

The first step of this work is the validation of the numerical procedure on a simple geometry for two different materials (copper and tungsten) and constitutive material models. In particular, the high energy particle impact is examined on a facially irradiated cylindrical bar: the beam hits the component directly on the centre of the basis. Then the final step is the study of the impact on a real structure with an energy beam of 5 TeV (the next target in the energy value of LHC beam).

Introduction

The LHC is a circular accelerator with a 26.659 km circumference situated at the border between Switzerland and France at an average depth of 100 m underground. This machine mainly provides the collision between two counter-circulating proton beams. At the design operating condition, each proton beam consists of 3×10^{14} protons at 7 TeV, so when the protons collide the collision energy is 14 TeV. The beam has 2808 bunches each having 1.11×10^{11} protons. The bunch length is 0.5 ns and the time between two successive bunches is 25 ns, so the duration of the entire beam is about 72 μ s.

The total energy stored in each beam at maximum energy is about 350 MJ: this is enough energy to melt 500 kg of copper. This large amount of energy is potentially destructive for accelerator equipments having direct interaction with particles (e.g. the collimation system) in case of uncontrolled beam loss, so everything is done to ensure that this never happens. Besides, it is important to know what will be the damage in case of the LHC malfunction. It is in this perspective that a thermo-mechanical analysis becomes relevant. However, it is very difficult to predict structural efficiency and robustness accurately: beam-induced damage for high energy and high intensity occurs in a regime where, nowadays, practical experience does not exist. For now the importance of developing a reliable multidisciplinary methods (physics, hydrodynamics and structural engineering are involved) and accurate models that could be efficiently applied to estimate the damage occurring during an impact is therefore evident (Fig. 1).

The interaction between high energy particle beams and solids can be considered from a structural point of view as an energy deposition inducing a sudden non uniform temperature increase. This provokes a dynamic response of the structure entailing thermal stress waves and thermally induced shock vibrations or even the failure of the component. The pressure and temperature increase and the material could arrive at its melting temperature or vaporize. The remaining part of the material is characterized by high values of plastic strain, strain-rate and temperature.

Fig. 1. High energy particle beam impact effects on a metal structure

Effects of high energy particle beam

In case of interaction between a high energy particle (protons) beam and a metallic material three main dynamic response regimes may occur, depending on the deposited energy, the energy density, the interaction duration and the material strength. The first possibility is the case in which the induced stress waves and the vibrations remain in the elastic domain. In this case the deposited energy density is low, the changes in density are negligible and the stress waves travel in the material at the sound speed. On the other hand, for medium energy levels, the stress waves are generated in the plastic domain. This implies the velocity of the waves is lower than the elastic domain speed and there are permanent deformations in the component also once the load is over. The last case implies that a large amount of energy is delivered on the component. In the matter there is the dawn of shock waves, in which there is a nearly discontinuous change in the characteristic of the medium (pressure, temperature and density). The discontinuity moves with a supersonic velocity and this makes the mass transport phenomenon to be relevant.

Fig. 2. Energy distribution (GJ/m^3) on a cylindrical component (radius of 10 mm, length of 1 m) in copper (left) and tungsten (right) for a single bunch at 7 TeV

In order to correctly simulate the effects of the high energy particle interaction with a solid target, it is necessary to calculate the energy deposition on the component delivered during the impact duration. In this work the calculation is done from the physicist at CERN via the statistical code FLUKA [1]. FLUKA is a fully integrated package for the calculation of particle transport and interaction with the matter, based on the Monte-Carlo analysis with many applications in high energy experimental physics and engineering. The FLUKA result (Fig. 2) is the energy map on the same geometry on which the numerical simulation is performed.

Hydrodynamic and deviatoric behaviour

An equation of state (EOS) is a constitutive relation between state variables and describes the state of the matter. Usually it expresses a thermodynamic variable (such as pressure or internal energy) in function of two other independent state variables (such as density and temperature). In this work a tabular multi-phase equation of state [2] is used. In particular, solid, liquid, vapour, gas and plasma region are taken into account. In Figure 3 the P - ρ - T space for tungsten is depicted.

Once the energy for the impact of a proton bunch is known, it is possible to understand the consequent material behaviour considering the EOS in the P - E plane varying the density (Fig. 3). The arrival of the bunch pulse, obviously, modified the precedent matter condition: in particular, there is an increment in the energy of the medium. Since the impact duration is quite small, it can be considered as an isochoric transformation, so the jump in energy is done along the density curve characteristic of the previous state. This implies a new value in pressure univocally identified from the new energy and density conditions. The global result is that instantaneously the material reaches a different (greater) pressure. This, together with the fact that for this problem different parts of the component are not in the same condition, a shock front is generated: the elements with a high level of pressure rapidly expand into the elements with a low level.

Fig. 3. Equation of state for tungsten in the P - ρ - T space (left) and for copper in the P - E plane varying the density (right): thermodynamic behaviour consequent to high energy deposition

In past decades a lot of material models for the description of the deviatoric behaviour are proposed. The Johnson-Cook (J-C) model [3] is a purely empirical model; an example of semi-empirical model is the Steinberg-Cochran-Guinan-Lund model, which was first (S-G) developed for the description of high strain-rates behaviour [4], and after (S-L) extended to low strain-rates [5].

In this work a first set of simulations is carried out with the J-C [3] model because also if it very simple it is able to predict the mechanical behaviour of the materials under different loading conditions. Besides, it is one of the most used material model, so it is implemented in many FEM codes and it is quite easy to find the values of J-C parameters for different materials. Nevertheless, the J-C model is quite inaccurate to describe the material behaviour in case of high pressure conditions. As a matter of fact, it neglects the influence of the pressure and changes in volume on the flow stress and it considers the melting temperature as a constant, while the solid-liquid transition is influenced by the density. A more suitable model is the S-G material model [4] in which the strength material characterization is controlled by the equations

$$\sigma_y = \sigma_A \frac{G}{G_0} \quad \sigma_A = \sigma_0 \left[1 + \beta (\varepsilon_{pl,i} + \varepsilon_{pl}) \right]^n \leq \sigma_{\max} \quad \frac{G}{G_0} = \left[1 + b P v^{1/3} - h (T - 300) \right] \quad (1)$$

$$T_m = T_{m0} \exp[2a(1 - v)] v^{-2(\gamma_0 - a - 1/3)}$$

in which both the flow stress and the shear modulus are function of temperature, strain and also pressure, v is the relative volume, b and n are the work-hardening parameters and $\varepsilon_{pl,i}$ is the initial equivalent plastic strain, normally equal to zero. The subscript 0 refers to the condition in which $T=300$ K, $P=0$ and $\varepsilon=0$, the reference state. b and h are proportional to the derivative of the yield stress respect to the pressure and to the derivative of the shear modulus respect to the temperature, respectively. As in the J-C model, if the temperature overcomes the melting temperature then the

material strength goes to zero, but differently from the J-C model, the melting temperature is not constant but is a density function. The S-G model is strain-rate independent, according to the fact that for strain-rates greater than 10^5 s^{-1} the rapid decrease of rate dependent effects with increasing dynamic stress may be explained by the increase in temperature with increasing stress [4]. This assumption is reasonable in case of FCC material, like copper, but could be inaccurate in case of BCC materials [5].

Benchmarking

The numerical simulations are performed via the commercial code LS-DYNA. The validation of the numerical results is performed on a simplified geometry: a cylindrical bar (radius of 10 mm and length of 1 m) facially irradiated by 8 bunches at 7 TeV ($\sigma_r = 0.088 \text{ mm}$), each of them having 1.11×10^{11} protons. A lagrangian 2D axis-symmetric model is used with an explicit time integration (time step magnitude 0.01 ns). A non reflection boundary condition is applied at the external radius.

Fig. 4. Pressure evolution for copper (top) and tungsten (bottom) components: radius ($\rightarrow$), length ($\uparrow$)

Fig. 5. Density evolution for tungsten component: radius ($\rightarrow$), length ($\uparrow$)

The results in terms of pressure, that are substantially independent from the chosen deviatoric material model, are reported in Fig. 4 and the comparison with the results of [6] for copper are satisfactory. A radial shock wave generated in the central/impact zone travels from the hit zone to the face. The levels of pressure reached at the end of the deposition ($\sim 200 \text{ ns}$) are very high. Since the intensity level of the beam is the same for the two materials, the difference in the pressure levels is essentially due to the difference in density: the greater the density the higher the energy

absorption. Fig. 5, shows the density evolution for tungsten: there is a rarefaction behind and a compression ahead the shock wave front. Due to the strong reduction in density, the material becomes gas and it is removed from the model (similar results are for copper).

In Fig. 6, an overview of the results is reported. The pressure and the density at the end of the deposition act as a pump (or similarly an explosive) which produces a dynamic deformation of the material ahead the shock front. In the centre the Von Mises stress is zero because the temperature overcomes the melting value. In the remaining part of the component high levels of stress ($\sim 2 \sigma_0$), strain-rate (over 10^5 s^{-1}) and plastic strain (over 10%) are reached.

Fig. 6. Pressure and density distribution at the end of the deposition (left) and Von Mises, strain-rate and plastic strain at about $1 \mu\text{s}$ after the impact (right) for copper (top) and tungsten (bottom) components: radius ($\rightarrow$), length ($\uparrow$)

Three-dimensional real structure

The method is finally applied to simulate the beam impact against a real complex geometry: the Target Collimator Tertiary (TCT) of LHC [7]. The lagrangian 3D numerical model represents a simplified structure respect to the original one, but it considers the presence of two different material parts and the contact between the different model components. Substantially, the structure is a parallelepiped with an internal part made by tungsten (the hit part) and an external C-section in copper. The simulation provides the impact of 8 bunches each having 1.13×10^{11} protons at 5 TeV ($\sigma_x = 0.3 \text{ mm}$ and $\sigma_y = 0.19 \text{ mm}$). In Fig. 7 some simulation results are shown. During the deposition phase ($0 \div 200 \text{ ns}$) the pressure evolution is quite similar to the 2D cylindrical case. The reached level (156 GPa) is lower due to the different beam intensity and size. Once the deposition is finished a shock wave is generated and moves from the tungsten region to the copper part. Differently from 2D, in which the beam hits the centre of the structure, in this case the material is hit near a free surface. For this reason it can't create a wide zone of rarefaction because the pressure wave reaches in a short time the component free surface and is reflected: due to this the material is threw out. Since the significant difference in impedance between the two materials, the shock wave is in part reflected at the interface: this causes the spallation of tungsten ($P_{\text{cutoff}} = 900 \text{ MPa}$) and the reduction of the pressure level transmitted to copper. The material near the surface is projected toward the other TCT jaw at high velocity. The level of stress in the two part is very high (about 3 GPa in tungsten and 230 MPa in copper).

Fig. 7. 3D view of the TCT (left); simulation results at 4.2 μ s (right): pressure (max=5.96, min=-0.9 GPa), resultant velocity (max 1.54, min=0 km/s), Von Mises stress in tungsten (max 2.55, min=0 GPa) and Von Mises stress in copper (max 177.50, min=0 MPa).

Conclusions

This study was performed in order to estimate the damage on a metal component due to the impact with a proton beam generated by the Large Hadron Collider (LHC) at CERN. The case study represents an accidental case consequent to an abnormal release of the beam, in which 8 bunches irradiate the target directly. The energy delivered on the component was calculated using the FLUKA code and then used as input in the numerical simulation, that were carried out via the FEM code LS-DYNA.

In this kind of problems both the hydrostatic and the deviatoric components are involved, but in different regions of the hit component. The hydrostatic behaviour of the target was described using a multi-phase equation of state, while the elasto-plasticity response was treated using Johnson-Cook and Steinberg-Guinan material models.

In the first part, the validation of the numerical procedure on a simple geometry for two different materials (copper and tungsten) and constitutive material models was presented. In particular, the high energy particle impact was examined on a facially irradiated cylindrical bar: the beam hits the component directly on the centre of the basis. Then the final step was the study of the impact on a real structure with an energy beam of 5 TeV (the next target in the energy value of LHC beam).

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