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Explosion simulation of pressurized components

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Summary. This article describes a simulation study of engine components that operate in an explosion risk zone. High pressure system failures and unfavorable chemical reactions put components in situations not commonly considered in normal dimensioning. From the safety point of view, explosion and damage control involve a wide range of uncertainty factors.

Key words: safety, explosion simulation, FEM, damage

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Introduction

Where there is a mix of high pressure and gases, the probability for explosion must always be taken into account. Engines connected to pneumatic systems, a charge air system, fuel-, oil- and gas systems have common properties that can end up in hazardous situations. Materials in pressurized systems vary from high strength steel components to brittle cast iron components, which makes the system behavior very challenging. Sharp corners, dead ends, caps and all bolt connections play also a key role in the design. With the right combination of "fuel", the pressurized system can trigger a detonation with shock front velocities from 2000 to 6000 m/s and the impacts often lead to grenade-like structures. [7] One approach is to simulate the critical outcomes virtually by using finite element analysis. Dynamic simulation in combination with damage evolution provides a design tool to ensure safe components for the end user. [1, 2]

Unlike the fatigue and fretting phenomenon [4, 3, 5, 6], explosions are typically dimensioned against the ultimate tensile strength, meaning that, at a certain safety level, only one loading case is acceptable and afterwards some components need to be changed.

Damage evolution simulation

The source to the explosion is difficult to determine exactly in systems where the main factor is unknown. The soot explosion shock wave velocity is around 2500 m/s, while that of a dynamite explosion is 6500 m/s. On the simulation level, this means load step times in milliseconds. To model a shock wave going through the pressure line is challenging, and

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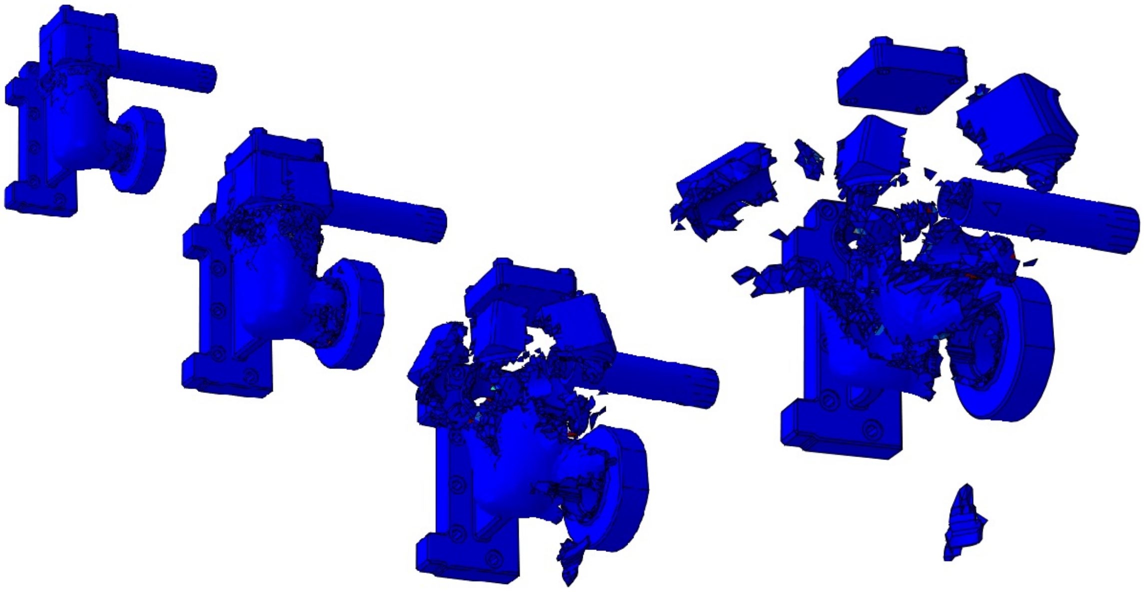

Figure 1. System damage evolution.

therefore the use of pressure surfaces is more practical when the speed and starting location of the explosion are unknown. The component is restrained from the bolt locations and inner volume is divided into several surfaces where the pressure is applied sequentially. Timing and order of the pressure loads can be defined according to assumed explosion speed and starting location. Progressive damage and failure is modeled in three stages, damage initiation, damage evolution and element removal. Damage initiation criteria consists of two equivalent plastic strain components, ductile and shear shown in equation (1). Initiation criterion for ductile or shear component is met when [2]

$$\omega_D = \int \frac{\mathrm{d}\overline{\varepsilon}^{pl}}{\overline{\varepsilon}^{pl}_D(\eta, \dot{\overline{\varepsilon}}^{pl})} = 1 \qquad \text{or} \qquad \omega_S = \int \frac{\mathrm{d}\overline{\varepsilon}^{pl}}{\overline{\varepsilon}^{pl}_S(\theta_S, \dot{\overline{\varepsilon}}^{pl})} = 1, \tag{1}$$

where η is stress triaxiality, $\overline{\varepsilon}^{pl}$ is equivalent plastic strain, θ_S is shear stress ratio. Once the damage initiation criterion is met, the stiffness degradation or damage variable d is defined as a function of effective plastic displacement shown in equation (2).

$$\dot{d} = \frac{L\dot{\overline{\varepsilon}}^{pl}}{\overline{u}^{pl}_f} = \frac{\dot{\overline{u}}^{pl}}{\overline{u}^{pl}_f}, \tag{2}$$

where L is characteristic element length and $\overline{u}^{pl}_f$ is the equivalent displacement at failure. When a specified limit value of d is reached the element is removed from the analysis.

Conclusions

This article describes a simulation study of engine components that operate in an explosion risk zone. High pressure system failures and unfavorable chemical reactions put components in situations not commonly considered in normal dimensioning. From the safety point of view, explosion and damage control involve a wide range of uncertainty factors, which makes these kind of modeling very challenging.

In the future, more material testing is needed in order to get correct material parameters for the damage model. Another improvement could be CFD simulations of the explosions in order to get more accurate internal loading conditions of the traveling pressure wave.

However, the methodology described in this paper is promising in the way that it enables simulation of these kind of extreme loading cases in reasonable time. Wärtsilä always considers human safety to be the most important design factor as well as is constantly looking methods to improve it.

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