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Failure analysis and finite element simulation of deformation and fracture of an exploded CNG fuel tank

Majid Mirzaei *, Mohammad Malekan, Ehsan Sheibani

Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran

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ABSTRACT

This paper reports the analysis and simulation of the catastrophic failure of a compressed natural gas (CNG) fuel tank. The initial analyses of the deformation and cracking patterns, along with the observed fractographic features, were indicative of an internal gaseous combustion. Accordingly, a set of transient-dynamic elasto-plastic finite element (FE) analyses was carried out to simulate the structural response of the tank to a special type of combustion-induced dynamic pressure. The FE model was composed of 3D brick elements equipped with interface cohesive elements for crack growth analysis. Excellent agreements were found between the final simulation results and the observed deformation and fracture patterns. The simulation results clearly revealed that the observed failure characteristics, like the overall *asymmetric* deformation and fracture patterns, initiation and partial growth of *parallel* cracks at the same section, *multiple cracking* at the neck, and the self-similar growth of the main axial crack were all caused by traveling of a *deflagration-induced sonic pressure wave* from the neck towards the bottom of the tank. Finally, a comparison was made between the characteristics of deflagration-induced and detonation-induced deformation and fracture behaviors of closed-end cylinders.

1. Introduction

The worldwide number of vehicles fueled by natural gas reached 15,000,000 in 2011, and the average annual growth rate of these vehicles in the ASIA–PACIFIC countries exceeded 38% [1]. The overwhelming majority of these vehicles use CNG (compressed natural gas) fuel tanks. Although the proper design, manufacture, quality control, transportation, and implementation of CNG cylinders have been specified by various standards and regulations [2–7], the number of accidental burst or even explosion of these cylinders is significant. Recently, the Civil Society Front Pakistan (CSF) has published a report, stating that more than 2000 people have died in CNG cylinder explosions in Pakistan in 2011, and the figures are more likely to double in 2012 [8]. In spite of the significant number of reported CNG cylinder explosions worldwide [9–12], the available reports on *systematic failure analysis* of these cases are quite scarce [13,14].

Currently four different types of tanks are in service (see Fig. 1). Type 1 is a simple seamless metallic cylinder [15], Type 2 is a metallic cylinder (liner) with an overwrap of carbon fiber or fiberglass in the hoop direction over the cylinder sidewall [15], Type 3 is a metallic cylinder with an overall (including the domes) overwrap of carbon fiber or fiberglass [16], and Type 4 is a non-metallic cylinder with an overall (including the domes) overwrap of carbon fiber or fiberglass [17]. In 2009 a *Type 1* tank exploded on board a sedan during refilling in a gas station in Iran. As a result of this catastrophic failure the car was partially destructed as shown in Fig. 2. Fortunately, the car had been evacuated prior to refilling so the incident did not cause

* Corresponding author. Tel.: +98 21 82883357; fax: +98 21 82880000.
E-mail addresses: mmirzaei@modares.ac.ir, majidmirzaei@hotmail.com (M. Mirzaei).

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Nomenclature

D	cylinder diameter (mm)
E	Young's modulus (GPa)
G_c	critical energy release rate (kN/m)
h	thickness (mm)
K_c	plane stress fracture toughness (MPa $\sqrt{m}$)
L	cylinder length (mm)
P	pressure (MPa)
t	time (s)
V	speed (m/s)
σ_u	ultimate strength (MPa)
σ_{ys}	yield strength (MPa)
Γ_c	cohesive fracture energy (kN/m)
ρ	density (kg/m^3)
Δa_b	backward crack growth (mm)
Δa_f	forward crack growth (mm)
v	Poisson's ratio

any injuries. As shown in Fig. 2 the explosion partially destroyed the rear part of the car but there was no burn marks on the wreckage. As the CNG tank ruptures usually lead to the outer combustion of the leaked gases, this simple observation was an initial indication of the fuel consumption prior to the burst of the tank. Moreover, the cracking pattern of the tank, along with a few specific features of the crack initiation and growth, indicated that this failure was not caused under normal operation

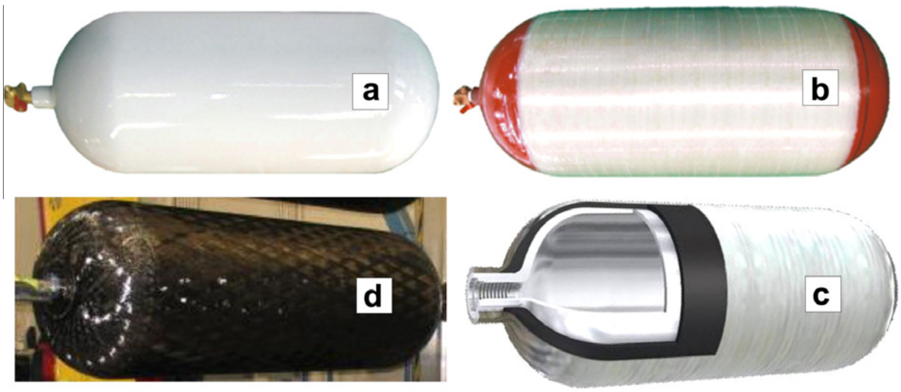

Fig. 1. Four different types of CNG cylinders. (a) Type I (seamless metallic cylinder), (b) Type II (metallic cylinder with an overwrap of carbon fiber or fiberglass in the hoop direction over the cylinder sidewall) [15]. (c) Type III (metallic cylinder with an overall overwrap of carbon fiber or fiberglass) [16]. (d) Type IV (non-metallic cylinder with an overall overwrap of carbon fiber or fiberglass) [17].

Fig. 2. Left: the wreckage of the car after the explosion. Right: the ruptured CNG tank. No burn mark was found on the wreckage.

and/or by manufacturing flaws, and it seemed highly probable that the tank experienced an excessive internal pressure caused by internal gaseous *deflagration* prior to the rupture. Deflagrations are combustion events in which the speed of the combustion wave front is subsonic. A deflagration explosion is less severe than a detonation explosion (with supersonic wave front) since the pressure waves are much weaker. However, the occurrence of internal combustion in an ordinary CNG tank during refilling seems peculiar because such combustion needs a proper mixture of fuel and oxidant. Although there have been several studies on *detonation-driven* fracture of tubes and cylinders [18–22], and despite the observations of natural gas deflagration in piping [23], there has been no report on dynamic stress analysis and fracture simulation of cylindrical tubes under *deflagration* loadings. This paper reports the major activities carried out to analyze and simulate the deformation and fracture processes that occurred during this particular type of failure.

2. Failure analysis based on the fracture pattern and surfaces

The overall fracture pattern of the tank, as depicted in Fig. 3a, represented an *asymmetric* initiation and growth of the main crack with respect to the midsection of the tank. This was in contrast to the usual burst pattern of these tanks due to overpressure, which naturally initiates at the midsection region and propagates towards the caps, creating an almost symmetric fracture pattern with respect to the midsection (Figs. 3b–d). Fig. 3b a typical symmetric rupture caused during the hydrostatic burst test of CNG cylinders using incompressible liquids. This type of loading naturally causes more inflation in the midsection which is less affected by the constraints imposed by the caps. Moreover the crack growth is stable and the crack arrest occurs because of the fast reduction in the energy release rate caused by leakage of a nearly *incompressible liquid*. Fig. 3c and 3d show two CNG incidents which occurred during refilling [24,25]. These cases show other types of symmetric burst caused by overpressure of gas which naturally leads to a more violent and unstable crack growth because the *compressed gas* can deliver energy to the crack even after the leakage. Based on the above arguments it was suggested that the cause of the observed asymmetric fracture was either a preexisting *flaw* outside the midsection or an *asymmetric pressure loading* (with respect to this section). In the next step, the chevron markings on the fracture surfaces were followed and the

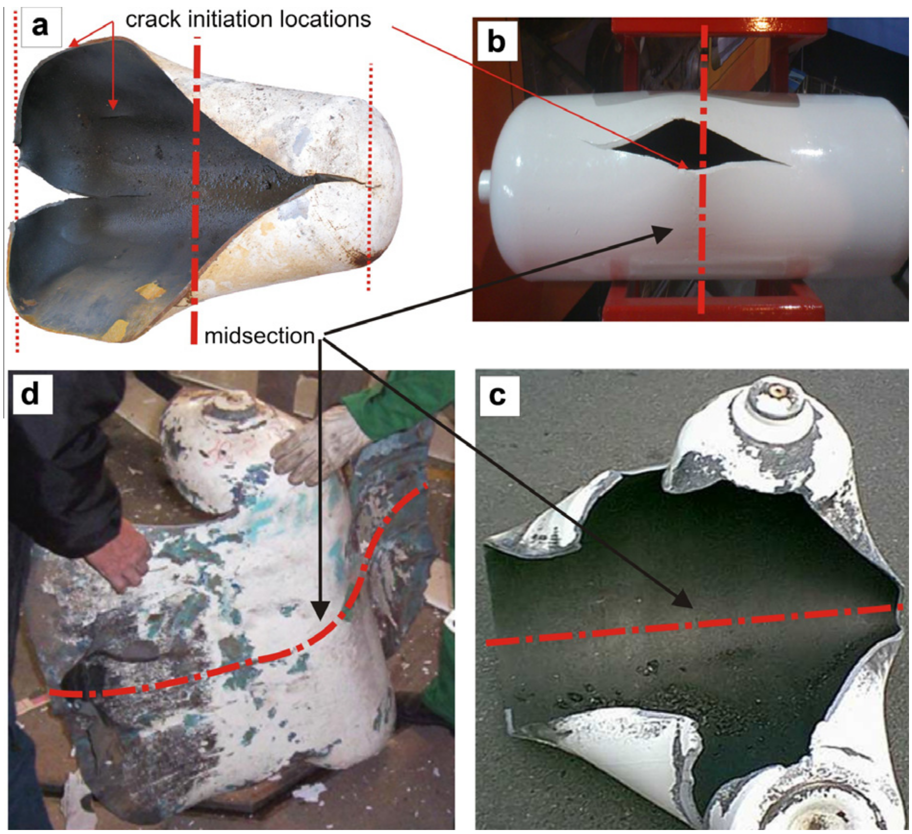

Fig. 3. Different types of CNG tank failure. (a) The asymmetric fracture pattern (with respect to the midsection) of the exploded tank. (b) Typical symmetric bulging and rupture of CNG tanks due to overpressure during hydrostatic testing. (c and d) Symmetric fracture patterns of two CNG tanks due to overpressure during refilling [24,25].

initiation site of the main crack was identified. This was below the neck portion of the tank and at the beginning of the cylindrical portion. Other very interesting features of this failure were the existence of parallel cracks at the same section of the tank and multiple small cracks just below the neck (see Fig. 4). The examination of the initiation site of the main and parallel cracks showed *no evidence of pre-cracking* caused by fatigue, stress corrosion, material defects, or manufacturing flaws. Moreover, examination of the wall thickness at different locations and measurement of the tensile properties of the cylinder showed that these quantities were within the standard range (see Table 1). Accordingly, the application of an asymmetric loading with respect to the midsection was considered as a plausible scenario. The chevron markings on the crack surfaces was used to specify the cracking pattern of the cylinder and the directions of crack growth as depicted in Fig. 4. The self similar growth of the main crack was in both directions towards the head and the bottom of the tank. The upper front of this crack continued growing until it severed the neck from one side and the growth of the lower front sized near the center of the bottom cap. Based on the above observations and analyses, it seemed plausible that this type of cracking was caused by an asymmetric loading such as a moving pressure traveling from the neck towards the bottom of the cap. In practice, this type of loading can occur either due to a sudden pressure rise at the neck by fast filling of a partially filled tank, or by initiation of an internal combustion of a flammable gaseous mixture at the neck. The former cause was discarded because the magnitude of such pressure wave can naturally be tolerated by a healthy cylinder. Since there was no proof that the cylinder was faulty, the latter cause was considered as the most plausible scenario for further investigation. As mentioned before, based on the type of combustion (deflagration or detonation), the speed of the moving pressure can be either subsonic or supersonic. However, the FE simulations of detonation-driven fracture of experimental tubes [22] and the evidences found on the fracture surfaces of an exploded gas cylinder containing hydrogen [20] showed that an important characteristic of the detonation-driven fracture of cylinders is that the crack propagation phase can be mostly or entirely driven by the *structural waves*. Thus, the whole cracking process and fragmentation can occur after the passage of detonation front. Among other features of detonation-driven fracture are a specific flap bulging process, the resultant crack branching, and the formation of special markings on the fracture surface which can be used to quantify the crack growth increments [20,21]. Since *neither of the above mentioned features* was distinguished on the failed fuel tank, it was suggested that the speed of the moving pressure was not supersonic and this failure could have occurred due to a subsonic *deflagration* of a gaseous mixture.

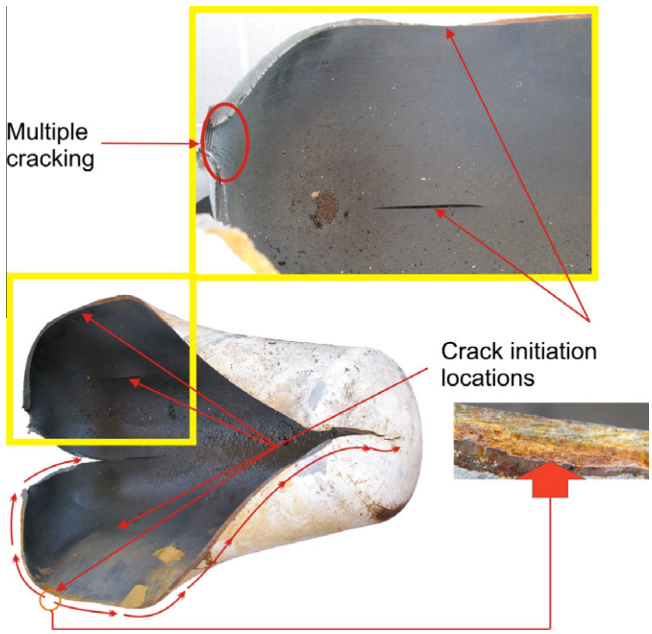

Fig. 4. Various features of deformation and fracture of the exploded tank. The crack initiation locations of the main and parallel cracks are pointed by arrows. The growth directions of the main crack are shown by double-arrows. The multiple cracking at the neck of the tank is shown by an ellipse.

Table 1
Physical and mechanical properties of the CNG tank material (34CrMo4).

ρ (kg/m^3)	E (GPa)	ν	σ_{ys} (MPa)	σ_u (MPa)	K_c (5.2 mm) (MPa $\sqrt{m}$)
8000	200	0.3	773	928	140

3. Failure analysis based on finite element simulation

Having conjectured the type of the pressure loading, the next step was the finite element simulation of deformation and fracture of the tank under the assumed moving pressure and calculation of the stress levels which caused the deformation and fracture of various parts of the cylinder. The relevant physical and mechanical properties of the material of the tank (34CrMo4 steel) are reported in Table 1. It should be mentioned that properties like yield strength and fracture toughness are rate-sensitive and their application to the high strain rates caused by gaseous and solid *detonations* usually requires proper adjustments [20]. However, since the strain rates caused by deflagrations are very much lower, the above correction was not necessary.

The FE simulation was carried out using the ABAQUS commercial package. A very crucial part of the simulation was the modeling and preconditioning of a moving pressure load with the required characteristics. In general, the profile and speed of the combustion front in a gaseous mixture depend on many parameters including the composition and pressure of the mixture. However, since the speed of the deflagration combustion front is subsonic and the resultant pressure wave travels at the sound speed, the loading history was preconditioned as a *sonic pressure front* as schematically depicted in Fig. 5. In brief, the loading scheme consisted of the application of a moving narrow ring pressure with the magnitude of 45 MPa, traveling at the speed of sound from the neck towards the bottom of the cylinder. It was also assumed that there was no significant pressure-wake behind the moving load because of the release of the combustion products by the crack opening. It should be noted that, since this moving pressure is axisymmetric and acts only in the radial direction of the cylinder, no fixities (displacement boundary conditions) were required in the FE model. A consistent set of transient elasto-plastic dynamic analyses was carried out to reach at the required accuracy and precision for the structural response of the tank to this type of dynamic loading. However, the initial FE solutions were obtained for low-pressure moving loads to keep the deformations within the linear elastic regime. The results were then compared with the available analytic solutions for the transient dynamic structural response of tubes to internal moving pressures [26–28]. As the accuracy of the model was checked and the mesh convergence was completed, the pressure was increased until the Von-Mises equivalent stress in the cylindrical portion of the tank exceeded the ultimate tensile strength of the material. The same moving pressure was later applied to the complete model equipped with interface cohesive elements. In general, the aim of these initial FE solutions was to finalize all the basic features of the model such as the appropriate mesh and the specifications of the moving load before proceeding towards the crack initiation and growth simulations. The outcome of this stage was a robust FE model with 56371 brick elements equipped with interface cohesive elements and a reliable moving load scheme. In general, the interface elements consist of two surfaces which connect the faces of two adjacent solid elements. The crack propagation occurs when the cohesive energy reaches a critical value (Γ_c). The cohesive energy for crack growth was computed as

$$\Gamma_c = G_c = K_c^2/E = 98\ \text{kJ/m}^2 \tag{1}$$

The overall dimensions of the model and the loading specifications are reported in Table 2.

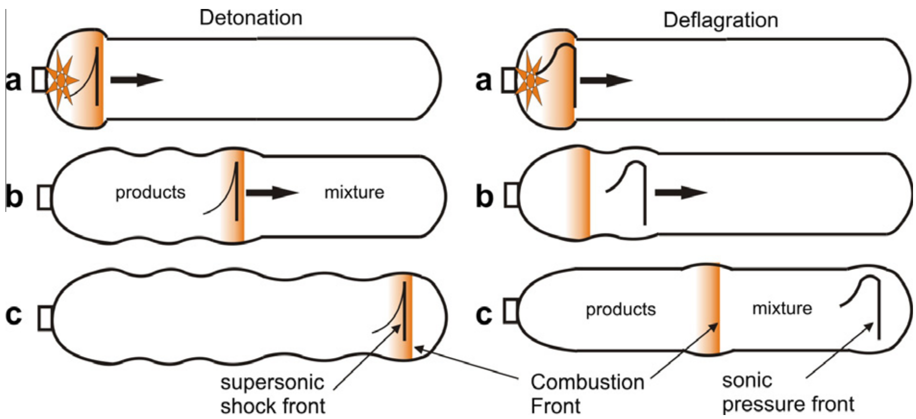

Fig. 5. Schematics of pressure loadings for two different types of internal gaseous combustions in closed-end cylinders. The amplitudes of deformations and structural waves are exaggerated for clarity.

Table 2
The overall dimensions of the model and the loading specifications.

D (mm)	h (mm)	L (mm)	P (MPa)	V (m/s)
232	5.2	860	45	343

4. Results and discussion

Fig. 6 depicts the results of the elasto-plastic transient-dynamic FE analysis of deformation and fracture of the tank, caused by traveling of a *sonic* pressure wave from the neck towards the bottom. The development of a ring stress which causes longitudinal parallel cracks at the beginning of the cylindrical portion of the tank is shown in Fig. 6b. This is the same location that the initiations of axial cracks were recognized on the exploded tank. The initiation and partial growth of parallel cracks at the same section can be attributed to the ring loading nature of the deflagration-induced moving pressure. Ideally, the ring loading is expected to cause axisymmetric radial displacements, strains, and stresses. In reality, however, the inherent *material heterogeneity* can cause local cracking at relatively weaker locations around the ring. In case of *high-pressure* moving fronts the parallel cracking is abundant and naturally leads to severe fragmentation. Nevertheless, for a *medium-pressure* sonic front the parallel crack growth can be aborted due to the fast consumption of strain energy by the advancement of a favorite crack. Fortunately, in the FE model, the inherent *numerical heterogeneity* of the mesh plays a similar role and the initiation and partial growth of parallel cracks can naturally occur as depicted in Fig. 6.

Another interesting feature of this failure is the existence of multiple small cracks at the neck. The FE simulation shows that these surface cracks were created by the concentration of bending stresses on each severed half of the neck. These stresses were in turn developed by the rapid movement of the flaps of the main crack in the opposite directions. The simulation also clearly shows that the neck was first ruptured on the front side by the self-similar growth of the main crack, and next on the back side as a result of the bending of the crack flaps.

In fact, the results of the FE simulation not only agreed with the initial hypothesis about the cause of this failure but also revealed some specific characteristics of the deflagration-induced fracture of closed-end cylinders. In the next section these characteristics will be compared with those previously reported for detonation-driven fracture of a similar cylinder [21].

4.1. A comparison between detonation-driven and deflagration-driven fracture of closed-end cylinders

Although both phenomena are driven by combustion-induced internal moving pressures, there are remarkable differences between the resultant deformation and fracture patterns. Fig. 7 depicts the snapshots of simulated crack growth

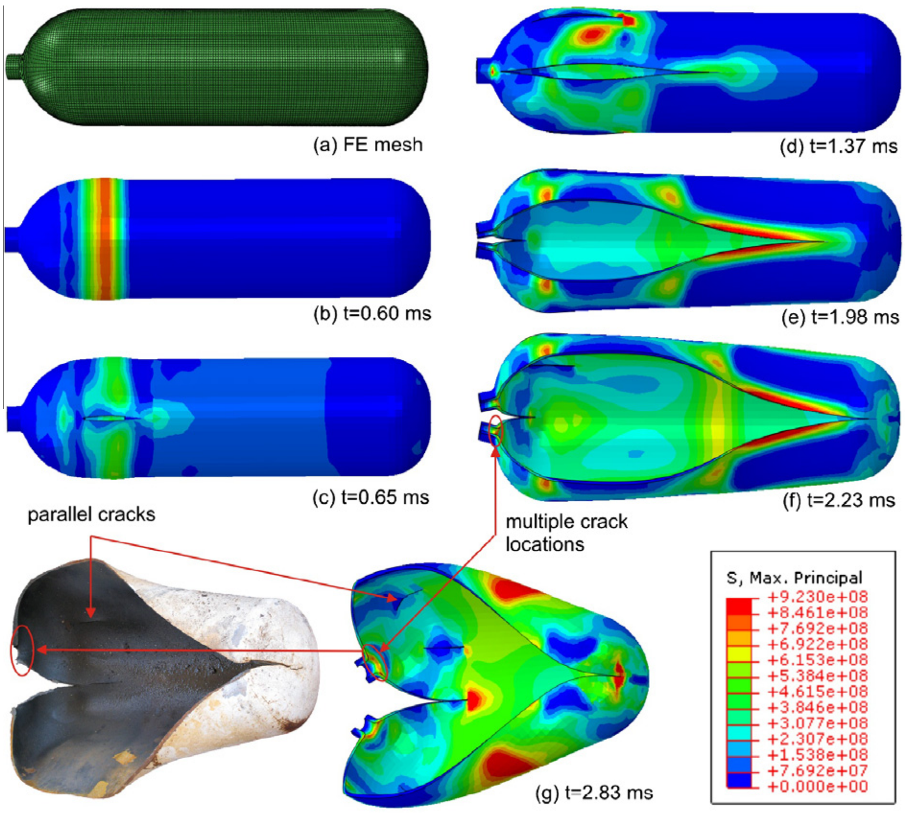

Fig. 6. FE simulation of deformation and fracture of the CNG tank. The snapshots show the initiation and growth of the main crack, the parallel cracks, and the multiple cracks caused by traveling of a *sonic* pressure wave from the neck towards the bottom of the tank. The snapshot (g) has been rotated to a viewpoint similar to the failed cylinder. The stresses are in MPa.

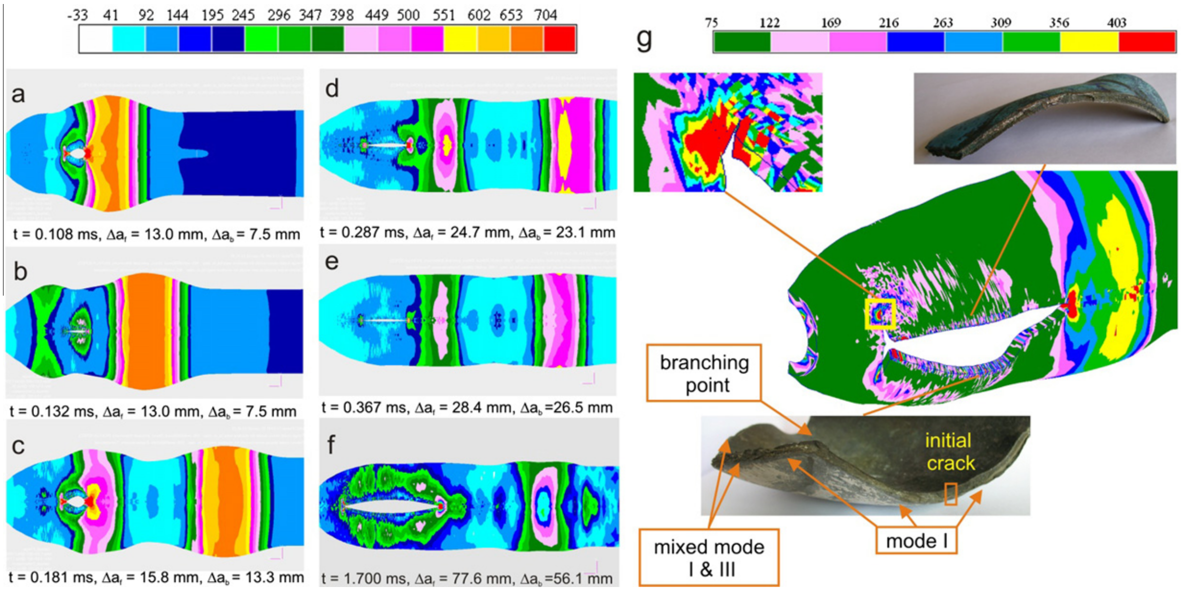

Fig. 7. FE simulation of deformation and fracture of an exploded hydrogen cylinder [21]. The snapshots show the crack initiation, the cyclic crack growth by structural waves, the cyclic flap bulging, and the resultant branching of an axial crack caused by traveling of a *supersonic* pressure wave from the neck towards the bottom of the cylinder. The stresses are in MPa.

caused by gaseous detonation in a hydrogen cylinder at different time intervals [21]. A distinctive characteristic of the structural response of a cylindrical tube to a detonation-induced *supersonic* pressure wave is the formation of flexural waves [26–28]. As depicted in Fig. 7, the successive opening and closing of the crack flaps is a clear indication of a *cyclic crack growth* governed by the flexural waves. This type of crack growth can create very distinct and specific markings on the fracture surfaces [20,21]. *In brief, the detonation-induced supersonic pressure wave excites the cylinder and the resulting flexural waves cause cyclic crack growth, whereas the crack growth caused by deflagration-induced sonic pressure wave is monotonic and driven by the pressure wave itself.* The above arguments can help to analyze similar failures in the future and also find answers for some of the questions posed in the past, like the reasons behind the accidents that occurred in the nuclear power plants in Japan and Germany in 2001 [29]. In both incidents, sections of steel steam pipes were fragmented due to combustion of hydrogen–oxygen mixtures created by radiolysis. One of the most important questions that arose during the accident investigation was whether the type of accidental combustion can be deduced from the fracture patterns. At that time, it seemed that the state of knowledge on combustion-driven fractures was not enough to answer this question.

5. Conclusion

This investigation was aimed at determination of the cause of the explosion of a CNG fuel tank during refilling. The general cracking pattern of the tank, the fractographic features, and the stress analysis results were all indicative of an internal gaseous combustion. Based on the above observations and using the results of the FE simulations of deformation and fracture of the tank it was concluded that the traveling of a *deflagration-induced sonic pressure wave* from the neck towards the bottom was the cause of this catastrophic failure. Moreover, several specific features of deflagration-induced fracture of such cylinders were specified. These features included the asymmetric fracture pattern with respect to the midsection of the tank, the initiation and partial growth of parallel cracks at the same section, the self similar growth of the main crack, and multiple cracking at the neck. The final comparison between the features of this deflagration-induced fracture with the previously reported results for detonation-induced fracture of a hydrogen cylinder has theoretical and practical applications. This comparison showed that in spite of the fact that both events are usually categorized as *combustion-induced explosions,* the effects of pressure wave speed on creation of *different* and *specific* deformation and fracture patterns for each combustion type are remarkable. Finally, a main conclusion of this investigation is that the occurrence of internal combustion in a fuel tank which was supposed to contain natural gas implies the existence of an oxidizer agent in the tank. Although the reason for the existence of air or other types of oxidant is not known yet, as a result of this investigation, a recommendation was issued for evaluation of the standard and safety measures in pertinent gas filling facilities.

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