

Application of Acoustic Emission Technology to Damage Analysis of High-Pressure Container for Fuel Cell Vehicles

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ABSTRACT

Evaluation tests are conducted in order to verify the design accuracy of vehicle-mounted high-pressure containers that use carbon fiber-reinforced plastic layers. We have developed a method to identify the state of damage generated in carbon fiber-reinforced plastic layers that eventually leads to bursting in these tests, in order to enhance the design accuracy of such containers.

For this method, we used acoustic emission technology and processed the measured results into dimensionless data. This enabled us to set threshold values for the appearance of major damage that is the prelude to bursting. For the first time in the world, this makes it possible to terminate the test directly before the bursting takes place.

Applying this technology will enhance the design of high-pressure containers by enabling a precise analysis of the state of damage in the carbon fiber-reinforced plastic layer of a high-pressure container.

1. Background and Purpose

In recent years, fuel cell systems have started to be considered and implemented as a source of electrical power in a range of applications, including for moving vehicles. Among such applications, fuel cells for vehicles are considered particularly promising, as such types of vehicles do not emit greenhouse gases during operation (see Fig. 1).

Recently in vehicle applications, it has become commonplace to store hydrogen, which serves as the fuel, as a high-pressure gas at 70 MPa. The high-pressure containers used are divided into four types, from Type 1 to Type 4, and are shown in Fig. 2.

Type 1 high-pressure containers are totally metal. Types 2 and 3 high-pressure containers are made with a metal liner surrounded by a layer of higher-strength carbon fiber-reinforced plastic (CFRP) in order to reduce size and weight. Finally, Type 4 high-pressure containers consist of a plastic liner surrounded by a CFRP layer. As Type 3 and Type 4 containers are compact and relatively lightweight, they are used as vehicle-mounted high-pressure containers. Currently, the Type 4 high-pressure container in particular is being widely used.

International standards are in place that stipulate the

necessary performance of vehicle-mounted high-pressure containers, including global unified standards relating to safety (Global Technical Regulation No. 13: GTR13)⁽¹⁾ and UN regulations (United Nations Regulation No. 134: UNR134)⁽²⁾. In Japan, while high-pressure containers are generally regulated by the High Pressure Gas Safety Act, the Act on Vehicles for Road Transportation regulates vehicle-mounted high-pressure containers. The international regulations mentioned previously have been ratified and are applicable under Japanese law.

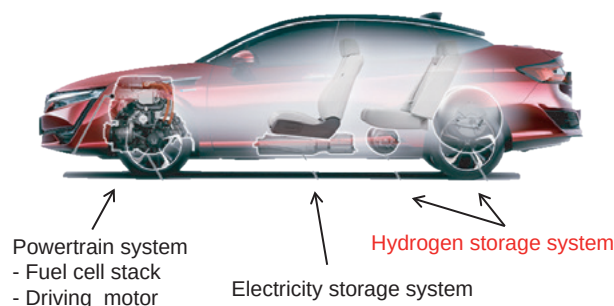


Fig. 1 Layout of major components of fuel cell vehicle

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The cost of high-pressure containers continues to be an issue in the widespread uptake of fuel cell vehicles (FCV)⁽³⁾. An effective way to reduce the cost of high-pressure containers is to reduce the use of expensive CFRP. As well, reducing the amount of material used helps to reduce the weight of the high-pressure container, and so various initiatives are being pursued for its achievement.

In basic terms, the amount of CFRP used depends on the ratio of the expected pressure to the carbon fiber (CF) strength. The functionality and durability of high-pressure containers are stipulated by laws and regulations. It is necessary to reduce the amount of CFRP as much as possible while still meeting these stipulations. Also, in order to achieve this, an important development task is to establish a high level of CFRP layer design technology.

The aim of our development was to establish a high-pressure container damage analysis technology to enhance the design precision of the CFRP layers of high-pressure containers.

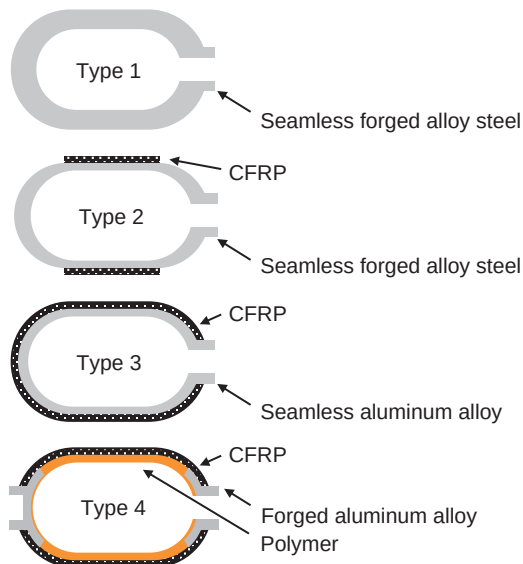


Fig. 2 Types and structures of high-pressure containers

2. Technology Development Goals

The accuracy of strength estimates and lifespan forecasts of the CFRP layers in high-pressure containers is not high. Therefore, the thickness of the CFRP layer is designed to provide a sufficient safety factor, and thus there is room to the design better by increasing accuracy.

Computer-aided engineering (CAE) is deployed in CFRP layer strength design. Based on this, prototype high-pressure containers are created and evaluated in testing, and the results are compared to the estimated values in order to enhance the accuracy of the forecasts. In other words,

the development is a repeated trial-and-error process, as depicted in Fig. 3.

In many cases, the high-pressure containers rupture into many small pieces, making it challenging to perform a detailed causal analysis of the origin and progression of the bursting of the prototype high-pressure containers. As a result, a high technological hurdle exists to feeding damage analysis results back into the design forecasting technology, creating a major challenge in improving CFRP layer strength forecasting technology.

It is important, therefore, to terminate the evaluation test just prior to the bursting of the high-pressure container, so that the state of the damage leading up to the final bursting can be properly understood. The methods for performing hydraulic pressure-induced burst tests and durability tests in high-pressure containers are stipulated in the GTR. Although the maximum pressurization rate in the tests is 1.4 MPa/s, many containers burst suddenly and without warning during the test, and in burst testing in particular, it is challenging to stop just prior to the burst.

Given the above, it was believed that the following technologies were additionally required.

- (1) Technology to terminate the test before bursting
- (2) Technology to identify the location of damage

In order to achieve this, the authors turned to acoustic emissions (AE) technology and enhanced the development process to enable detailed measurements of damage progression, as shown in Fig. 4. This report will focus on the particularly important first of the additional technologies mentioned above, (1) Technology to terminate the test before bursting.

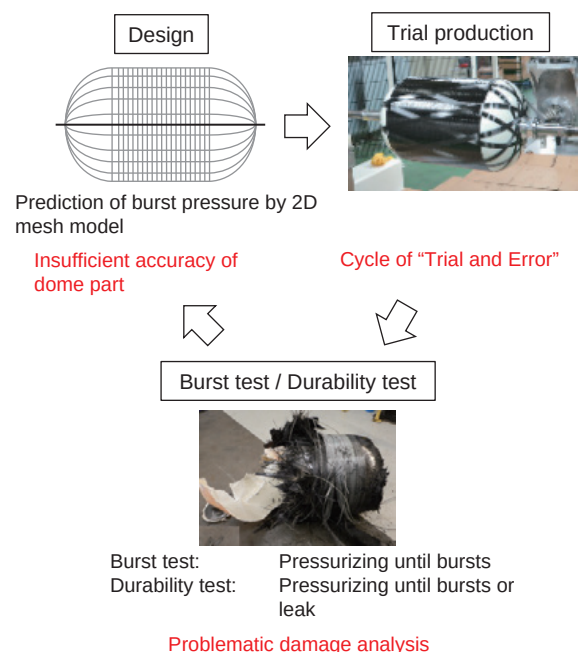


Fig. 3 Conventional high-pressure container development process

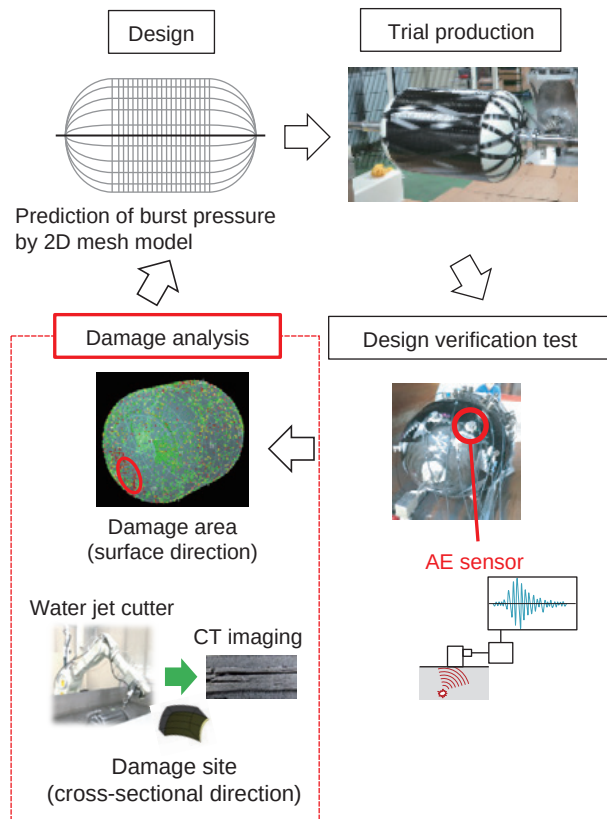


Fig. 4 Enhanced high-pressure container development process

3. AE Technology

AE technology⁽⁴⁾⁻⁽⁸⁾ is one of the technologies that are used for the nondestructive testing of structures, such as building structures or storage tanks. AE is a phenomenon in which the elastic energy stored within a structure is released as sound waves when that structure is deformed or damaged. AE waves refer to the elastic waves that travel through the target object and are detected. The strength and frequency of the sound waves vary according to the scale of damage and the material, and so they are often used to clarify the damage mechanisms of strengthening members.

AE waves are detected by sensors mounted on the surface of the high-pressure container and interpreted as a composite of multiple waves as shown in Fig. 5. Measurement noise can then be removed by setting appropriate threshold values, and the number of small waves that exceed the threshold value is defined as the count number. The energy of the AE waves is equivalent to the calculated surface area based on the AE wave duration time and amplitude.

In a high-pressure container, the CFRP layer is made of bundles of CF (filaments) with resin infused between the fibers. It is believed that damage to the CFRP layer

progresses according to a process like that shown in Fig. 6. Specifically, it is assumed that damage in the form of cracks and delamination in the resin forms in the early stages of use of the high-pressure container. As this increases and expands, the CF starts to undergo breakage, until finally the container bursts when a large amount of breakage has developed in the CF. By detecting the AE waves that are generated during this process, the authors believed it would be possible to analyze the process of damage to the CFRP layer.

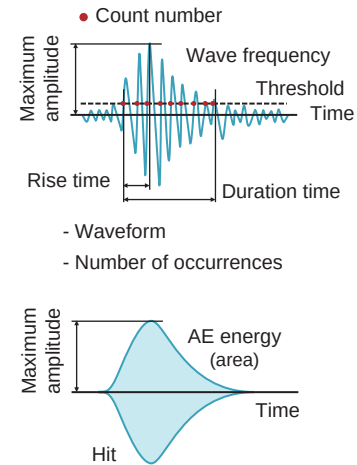
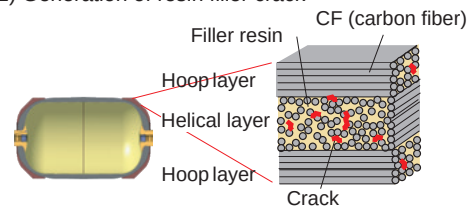
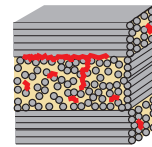


Fig. 5 AE waves and parameters

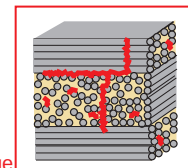
(1) Generation of resin filler crack



(2) Delamination and small breakage of CF



(3) Breakage of CF (transverse crack)



Just before burst:
Generation of
extensive CF breakage

(4) Burst

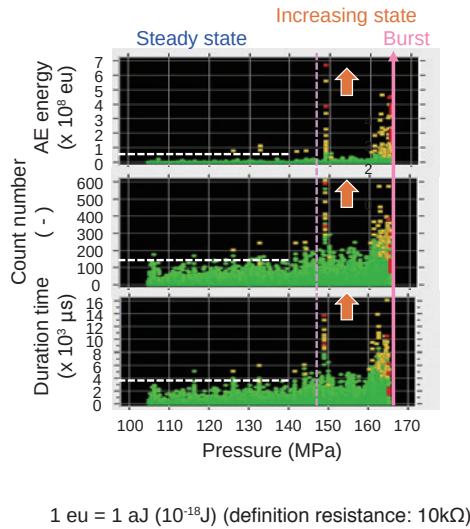
Fig. 6 Images of damage process in CFRP layer of high-pressure container

4. Technology Application and Results

To develop a technology that would use AE to stop a test just before bursting, hydraulic burst tests were conducted on vehicle-mounted high-pressure containers. In the hydraulic burst test, a high-pressure pump was used to fill and release water into and from a high-pressure container in order to change the internal pressure at a constant rate and thus evaluate the high-pressure container's strength and durability. The conditions were stipulated according to the high-pressure container codes and standards.

Two types of high-pressure containers were used in the tests, both sharing the same liner but with different CFRP layers. (Type A had an outer diameter of 530 mm and a length of 920 mm, while Type B was 550 mm and 920 mm, respectively.) In this report, the AE measuring devices, the measurement and analysis software, and the AE sensors were commercially available products. The templates needed to make the measurements, such as the basic shape of the measured object and propagation velocity, were as provided. (Measurement device: Vallen System MB19; Software: Vallen VisualAE R2019.0926.3; AE sensor: Vallen System VS150-RIC)

Figure 7 shows an example of the changes in the duration time, count number, and AE energy of the AE waves that were detected when the internal pressure of a Type A high-pressure container was increased at a constant rate. The horizontal axis shows the pressure in the high-pressure container, and the vertical axis shows the AE energy, count number, and duration time of the AE wave as detected from above. In the graph, AE waves with dimensionless AE energy from 20 up to less than 100 are



Red points: Dimensionless AE energy ≥ 100
Yellow points: Dimensionless AE energy ≥ 20

Fig. 7 AE detection status in burst test (high-pressure container: Type A)

shown as yellow dots, those of 100 or more are shown as red dots, and all others are shown as green dots. The dimensionless AE energy is as determined by Eq. (1) below.

The results show that as pressure increases, the highest values on the vertical axis remain almost constant (as marked by each chart's horizontal white dashed line) up to around 150 MPa, which is indicated by the vertical pink dashed line. A sudden increase in the values is observed around 150 MPa, and AE waves with steadily higher values are detected after this point, with greater pressures leading to an increasing number of yellow dots. Finally, bursting occurs at approximately 167 MPa, as indicated by the solid pink line, with an extremely large increase in the values.

The integrated count number and integrated AE energy results are shown in Fig. 8, making it easier to understand the circumstances leading up to bursting. The solid blue line shows the pressure in the high-pressure container for the given moment. The dot colors have the same meaning as in Fig. 7.

In the pressure range below approximately 150 MPa, the series of points starts by following a constant slope, as shown by the solid white line.

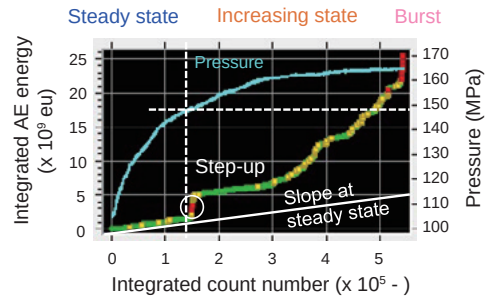
The line of points then rises abruptly and gradually increases thereafter. Eventually, there is another rapid rise, as seen in the upward solid red line, before bursting takes place.

The slope of the straight line in this Fig. 8 from the initial period up to an integrated count number of about 1.3×10^5 (at a pressure of about 150 MPa) represents the average AE energy of the small waves that make up the AE waves. After this, the linear relationship state as seen in the early stages of the test is defined as the steady state.

The same kind of test was conducted on several high-pressure containers of both Type A and Type B specifications, and the results are shown in Fig. 9.

As in Fig. 8, in Fig. 9 the slopes tend to rise at a constant rate from the start of the test up to a certain integrated count number.

However, the slopes of the steady-state straight lines obtained from the various high-pressure containers differ



Red points: Dimensionless AE energy ≥ 100
Yellow points: Dimensionless AE energy ≥ 20

Fig. 8 Changes of integrated energy and pressure in burst test (high-pressure container: Type A)

greatly. This is hypothesized to be caused by differences in sensor installation conditions and the ensuing sensitivity differences, AE propagation characteristics, and other variables. Therefore, to enable a unified comparative evaluation, we tried to standardize the slope of the straight line that is seen at the beginning of the pressure increases in Figs. 8 and 9.

By focusing on the average AE energy of all the waves that comprise the measured AE waves as shown in Fig. 5 and comparing it to the ratio of the average AE energy of the AE component waves under steady-state conditions, it was hypothesized that it would be possible to determine the severity of the damage in the CFRP layer. That is to say, the average value per AE energy count number at steady state was used to define the dimensionless AE energy according to the following formula.

$$\text{Dimensionless AE energy} = \left(\frac{E'}{\text{Count number}} \right) \bigg/ \left(\frac{\Sigma E'}{\Sigma \text{Count number}} \right)_{\text{Steady state}} \quad (1)$$

Here, E' is the AE energy calculated from the measured AE waves and is the apparent AE energy including various noise sources in the test and measurements, relative to the true AE energy (E).

Figure 10 shows the results of the measurements from Fig. 8 readjusted relative to the pressure and dimensionless AE energy. After taking an overall look at the various data such as high-pressure container burst pressures, the dimensionless AE energy at which a large amount of damage leading to bursting takes place was set at 100. Dimensionless AE energy was less than approximately 20 at steady-state conditions up to about 150 MPa. So, as in Figs. 7 and 8, in Fig. 10 steady-state dimensionless AE energy of less than 20 is shown with a green dot, AE energy from 20 up to less than 100, indicating major damage, is

shown with a yellow dot, and AE energy of 100 or more is shown with a red dot.

Figure 11 shows the results of the comparison between the burst pressure and the pressure that appears when dimensionless AE energy exceeding 100 appears in the measured AE waves, for the burst pressures that occur for the different high-pressure containers tested in burst tests. This figure shows that the ratio for all examples was less than 1. This confirms that the test could be stopped just before bursting if the threshold value for determining the dimensionless AE energy bursting is set appropriately. This technology has made it possible to secure a test object in a state just prior to bursting, making it possible to analyze the progression of damage with a detailed analysis of the CFRP layer.

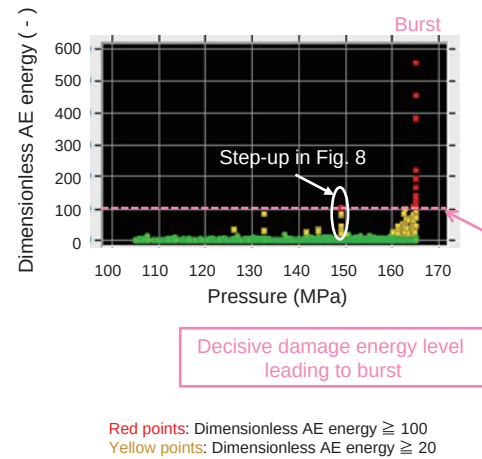


Fig. 10 Results of damage analysis using dimensionless AE energy (high-pressure container: Type A)

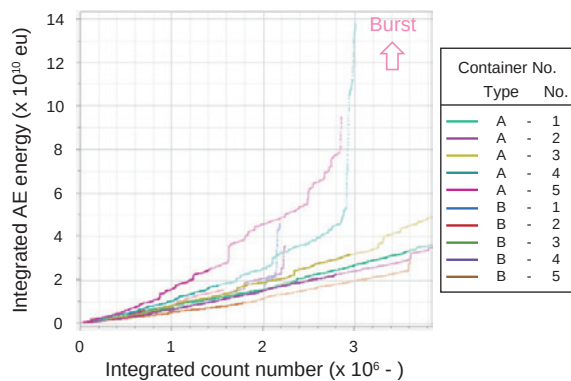


Fig. 9 Changes of integrated energy in burst tests of various high-pressure containers

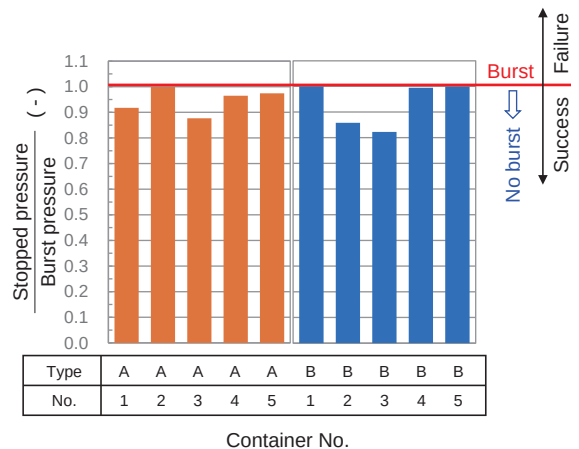


Fig. 11 Validation results of shutdown technology just before burst

5. Conclusion

In order to reduce the weight and cost of high-pressure containers mounted in fuel cell systems in moving vehicles, a high-accuracy CFRP layer design technology is required. To enhance the design accuracy, therefore, we have proposed a method using AE technology to identify the presence of CFRP layer damage that eventually leads to bursting in tests that can involve the bursting of high-pressure containers.

We focused on dimensionless AE energy and used experimental methods to exclude variations between high-pressure containers and individual tests, so as to establish a threshold value for shutdown decisions that can be applied to high-pressure tanks of a range of specifications. Using this value, we achieved a world-first technology to terminate a test just prior to bursting.

By providing a precise understanding of the damage process in the CFRP layer of high-pressure containers, this technology can be expected to enhance the design technology of high-pressure containers, reduce their weight and cost, and shorten development times.

As mentioned in Chapter 2, as well, we are studying technology to identify the location of damage by analyzing the differences in arrival times of the AE waves obtained in testing, as well as technology to identify damaged materials by analyzing the wave frequency of AE waves. We believe that this AE technology can contribute to further enhancements in design accuracy by advancing understanding of the damage process in CFRP layers in greater detail.

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