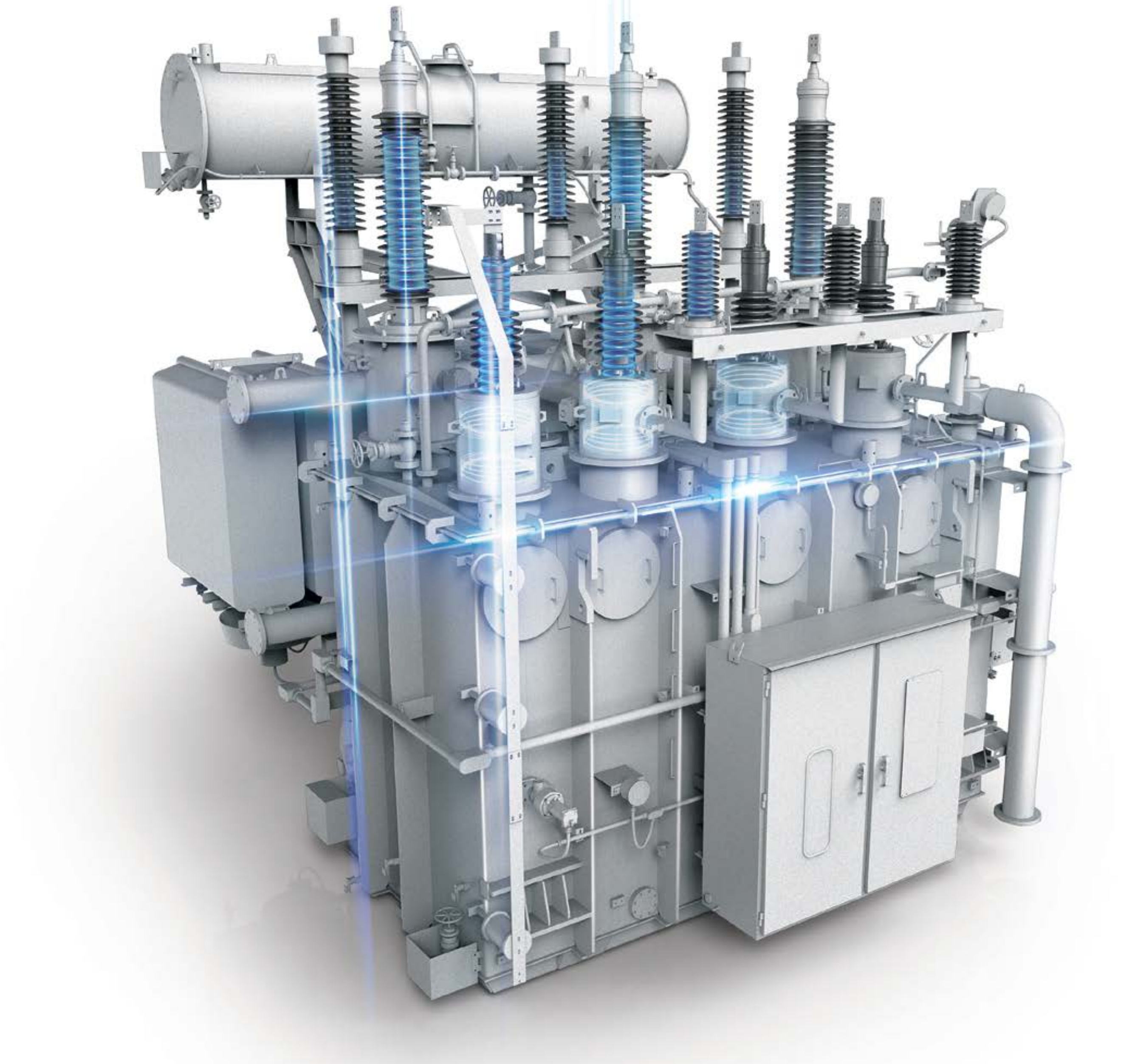


ABSTRACT

In general, a transformer is designed and manufactured to operate under normal conditions. However, unexpected fault events occur due to various reasons in real-life substations. When such events do occur, an electric arc inside a transformer vaporizes the insulating oil, leading to a generation of very high expansion pressure. Once this pressure exceeds the designed threshold, the tank is then compromised, and oil starts to leak, becoming a potential cause of fire or explosion.

DPRS (Dynamic Pressure Resistant System) transformer has been developed to cope with such unexpected events. In general, a PRD (Pressure Relief Device) is installed on a transformer to stabilize the pressure inside the tank. However, it requires a certain amount of time for this device to operate. DPRS transformer is designed to withstand the immediate pressure increase without severely damaging the tank (severe enough to cause an oil leak) until the PRD starts operating. Although not as much as to cause a leak, the tank will still be deformed as a result of the pressure increase. Then, insulating oil expanded by the arc is emitted safely through a designated path as the PRD starts to operate. DPRS transformer does not require additional equipment to prevent damage to the tank and is also capable of preventing fire while maintaining a similar configuration to common transformers. Due to these merits, the global demand for DPRS transformers is steadily increasing.

In the second part of this article, the fundamental criteria-defining research is presented, and additionally, a brief introduction to the explosion-proof performance verification test.

KEYWORDS:

arc explosion; pressure behaviour; dynamic analysis; explosion-proof test

Woo Hyun PARK, Jin Woo LEE, Sang Hoon CHUNG

> **The stiffeners are important components in absorbing pressure for DPRS transformers, and it is vital to understand the geometric characteristics of a stiffener**

DPRS transformer

Dynamic pressure resistant system - Part II

3. Fundamental research to define criteria

3.1 Construction of geometric database for stiffener's flexibility check

The stiffeners are important components in absorbing pressure for DPRS transformers. Hence, it is vital to understand the geometric characteristics of a stiffener. In order to verify the deflection and weak areas of a stiffener according to its shape, a bending test using a scaled-down specimen has been carried out. With this test, a database for each stiffener shape and its selection criterion has been established.

*Stiffener: a reinforcing structure attached to the tank wall to increase the strength and rigidity of the tank wall.

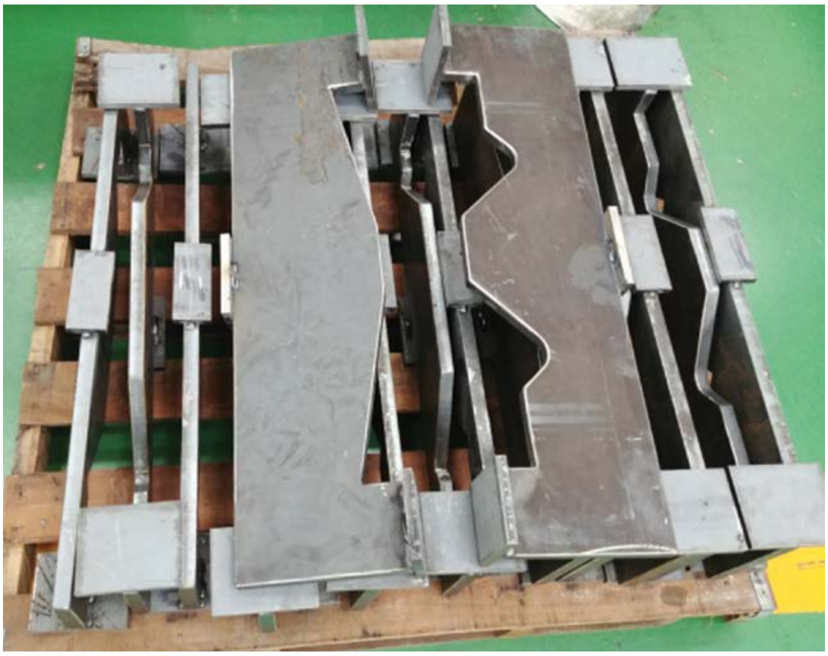


Figure 8. Stiffener flexibility check

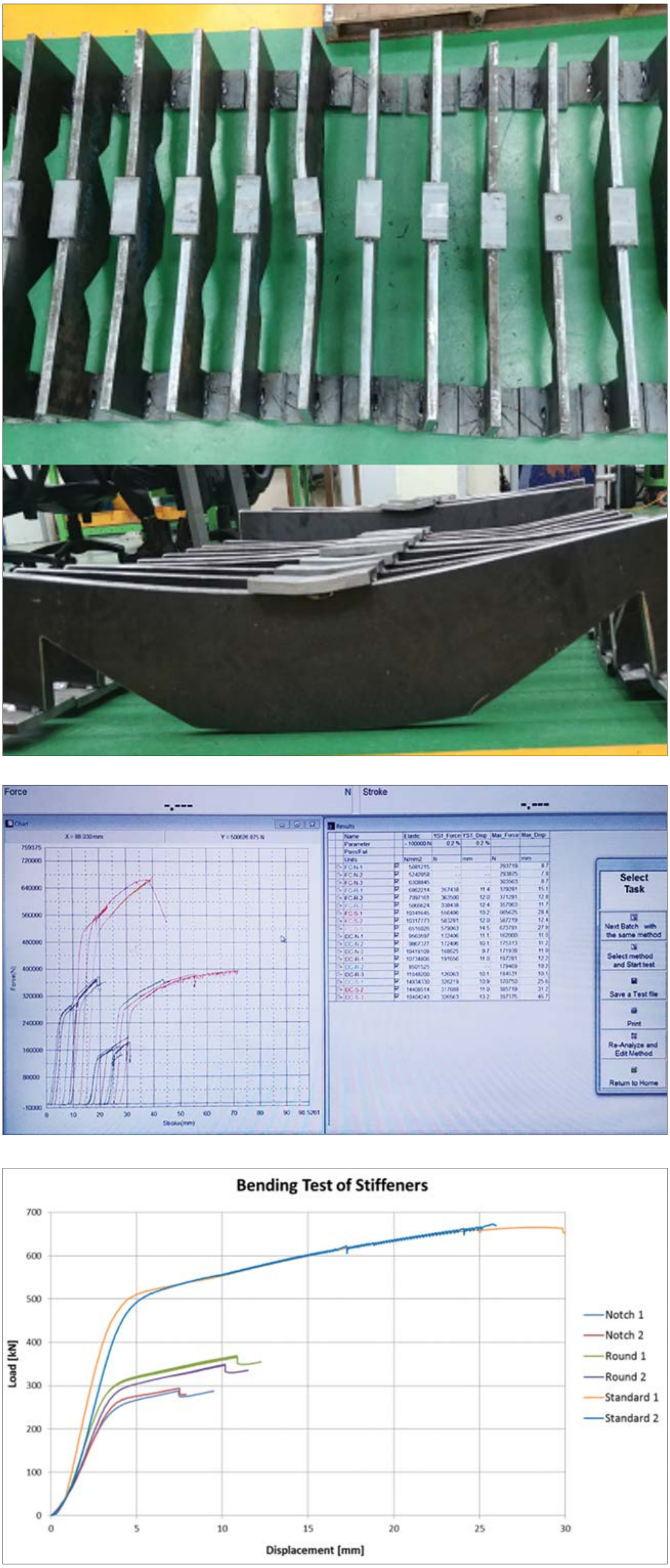


Figure 8. Stiffener flexibility check

3.2 Tensile test for ductile fracture criterion

A tensile test has been performed in order to establish the material's ductile fracture criterion. Tank and stiffener use the same steel. Hence, this test is intended for one steel with three different types which are described in the following sentence. Specimens with 3 different conditions were used: 1) with a notch, 2) without a notch, and 3) without a notch & welded. Johnson-Cook fracture model [3] presented with equation (3), was obtained by analyzing the correlation between stress triaxiality and fracture strain for each notch shape. The Johnson-Cook model is in a simple equation form, and material constants can easily be obtained through tests. It is a commonly used model in various fields for its usefulness in predicting the metal's impact and fracture behaviour.

$$\varepsilon_{p,f} = d_1 + d_2 \cdot exp\ (-d_3 \cdot \eta) \qquad (3)$$

< Johnson-Cook(J-C) Fracture Model >

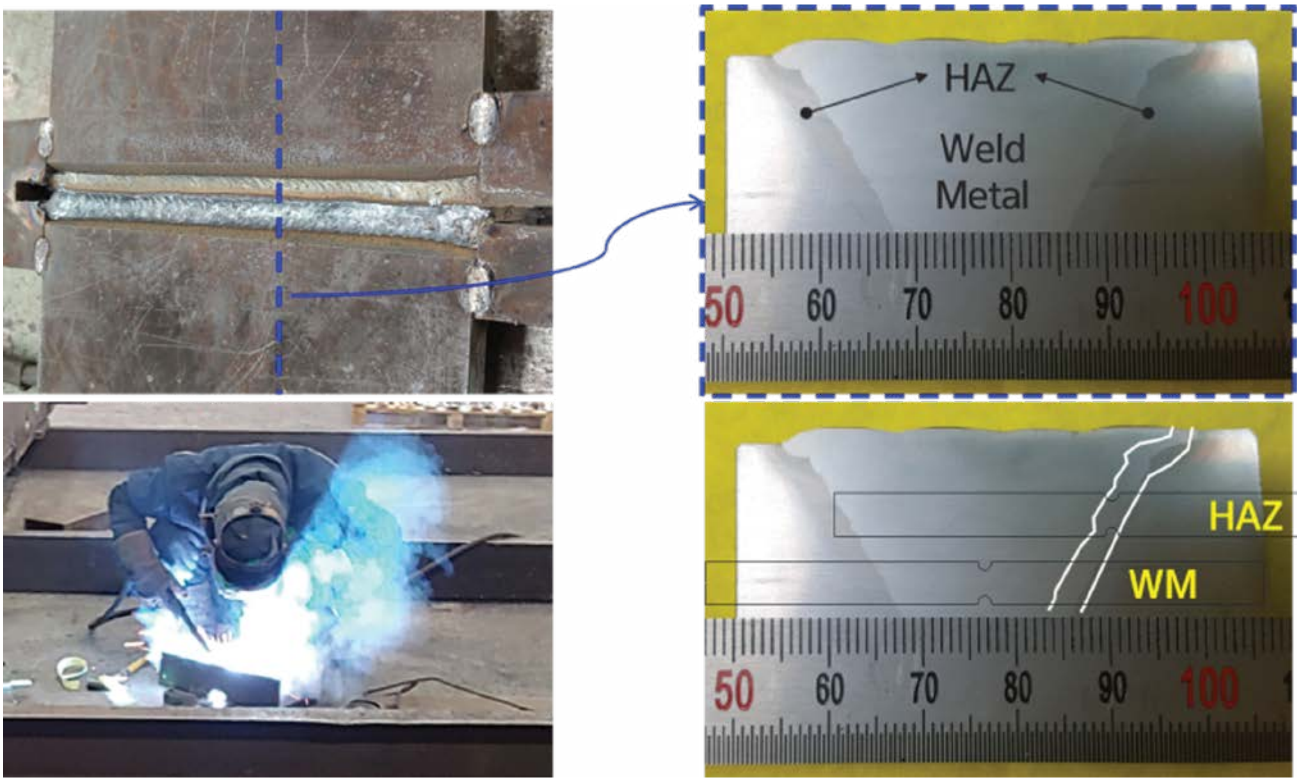
The parameters of equation (3) are as follows:

$\bar{\varepsilon}_{p,f}$ is the equivalent fracture plastic strain; d_1~d_3 is the material constants; η is stress triaxiality.

Understanding the dynamic behaviour of a material is an essential step in analyzing the DPRS transformer's structural characteristics and securing a robust design. This is because the accuracy of these properties and behaviour heavily impact the accuracy of the FEM results. In an effort to verify the Johnson-Cook model using the tensile test data, FEM simulating the tensile test has been carried out. The graph shows that the results of the two match with high similarity, and the obtained characteristics (through FEM) evaluate the material's behaviour more conservatively.

4. Verification test (explosion proof test)

In order to verify the reliability of the DPRS transformer design technologies introduced in earlier chapters, a verification test has been performed with an actual 500 kV DPRS transformer (tank size: approximately 5.0 m [height] x 3.0 m [width] x 5.0 m [length]). This kind of test has not been defined by any standard but is internally designed by Hyundai Electric.



Understanding the dynamic behaviour of a material is an essential step in analyzing the DPRS transformer's structural characteristics and securing a robust design

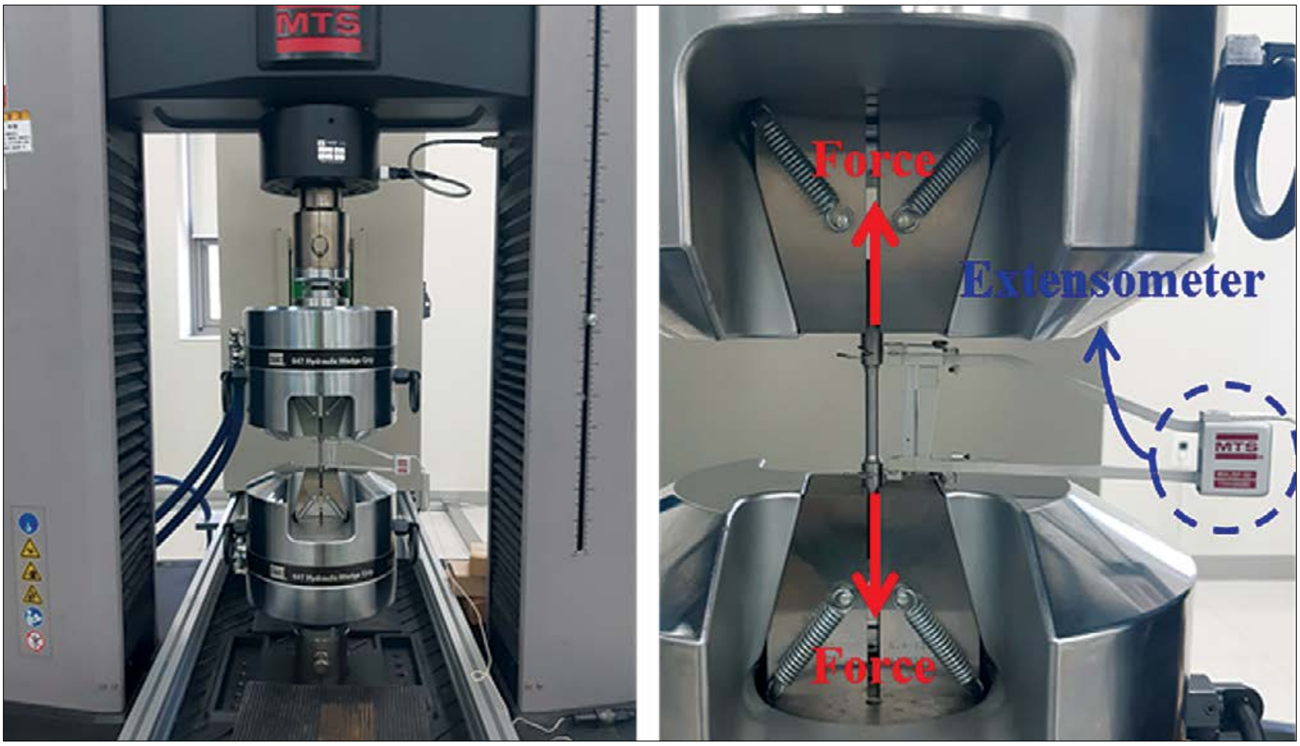


Figure 9. Tensile test for ductile fracture criterion

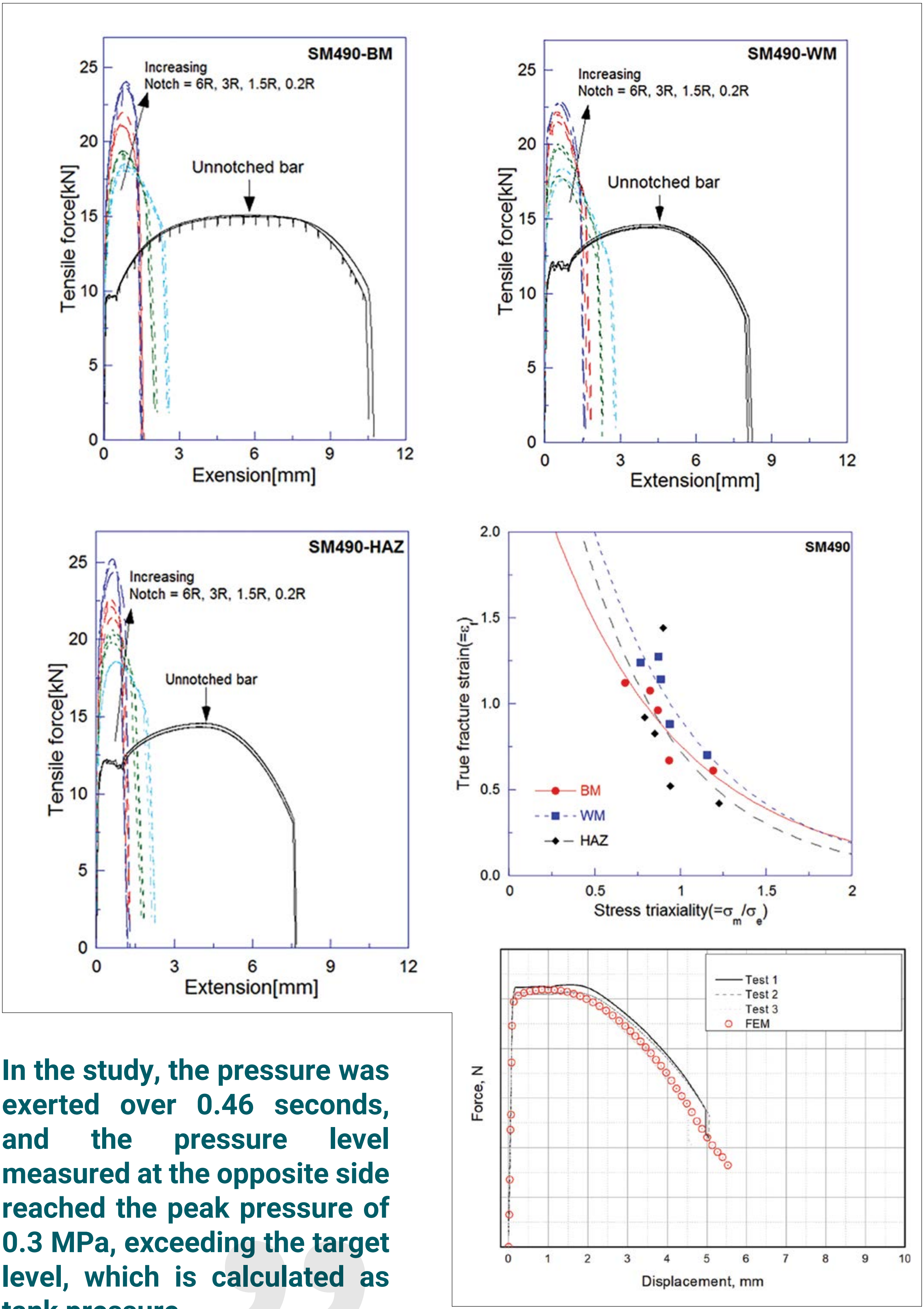


Figure 9. Tensile test for ductile fracture criterion

> **In the study, the pressure was exerted over 0.46 seconds, and the pressure level measured at the opposite side reached the peak pressure of 0.3 MPa, exceeding the target level, which is calculated as tank pressure**

> **In order to verify the reliability of the DPRS transformer design technologies introduced in earlier chapters, a verification test has been performed with an actual 500 kV DPRS transformer**

Along with the transformer test unit, a device capable of exerting pressure inside the tank within tens of milliseconds is required to simulate the actual arcing conditions. Additionally, sensors that measure the pressure on the tank and structural characteristics during the test were installed. Five pressure gauges were installed to measure the internal pressure of the tank, and a total of four contact and non-contact (laser) displacement meters were installed to measure the deformation of the tank.

The test duration without PRD operation was set at 0.5 seconds which is longer than the common PRD response time of 4~6 ms. The designed value for the internal pressure was 0.29 MPa at 10.5 MJ of arc energy. One of the other important aspects of this test is to develop a pressurization device capable of exerting the target pressure level on the tank interior without leakage. The design of this device, including the connection part to the tank, was verified through simulations and the unit was successfully built with trial and error. The test was successfully performed using the transformer unit and the pressure-exerting device.

4.1 Conclusion of verification test

The results of the test were evaluated based on the test data. The pressure was exerted over 0.46 seconds, and the pressure level measured at the opposite side reached the peak pressure of 0.3 MPa, exceeding the target level, which is calculated as tank pressure. The maximum deformation was measured to be approximately 38.4 mm at a 9 mm thick tank wall. The thickness of the tank wall is uniform at 9 mm, while

Figure 10. Explosion-proof test

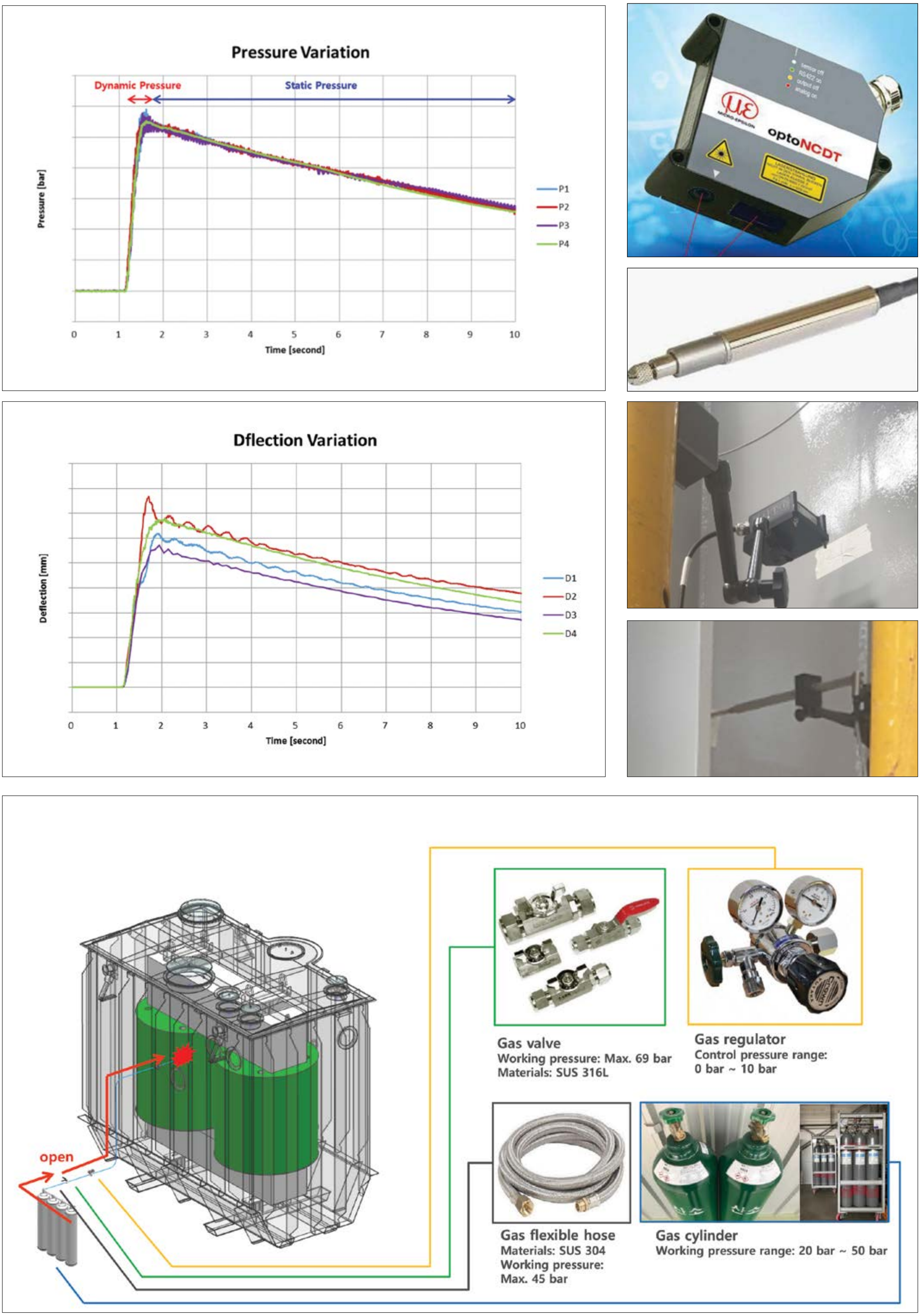


Figure 10. Explosion-proof test

> The DPRS transformer is capable of safely emitting insulating oil through a designated path during unexpected fault events, which significantly reduces the risk of transformer damage

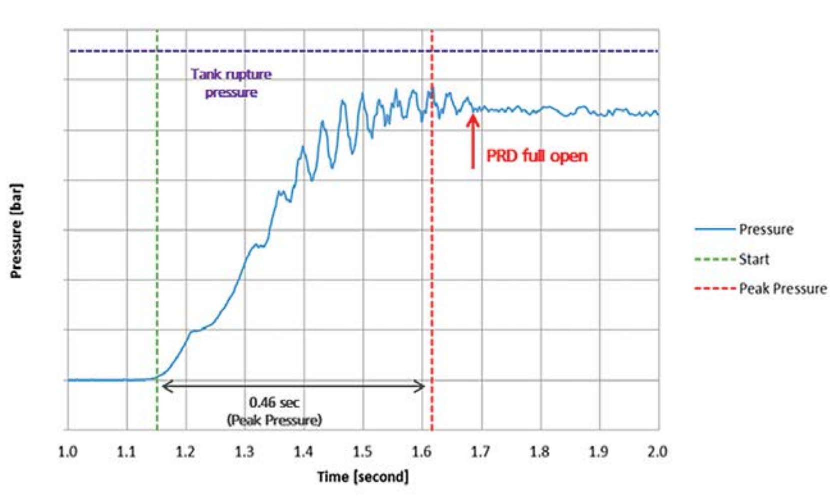


Figure 11. Internal tank pressure variation at the pressurized moment

that of the stiffener is 20 mm. It was confirmed during the test that the tank and stiffeners had undergone deformation due to absorbing internal pressure without any damage.

Also, an external inspection has been performed to confirm that the tank has not been damaged.

After reaching the peak pressure, PRD started its operation, and the insulating oil was emitted through a designated path. Through this test, the structural safety of the DPRS transformer tank designed and manufactured based on the technologies introduced in this article has been demonstrated along with PRD's normal operation.

5. Conclusion

In this article, the DPRS transformer, which is capable of safely emitting insulating oil through a designated path during unexpected fault events, has been introduced. Without such design, additional devices had to be installed around the transformer units to prepare for unexpected fault events, creating the need for a larger installation area and higher cost. However, the DPRS transformer has no risk of having its tank damaged during the fault events while maintaining its typical form, thus eliminating the need for additional area and cost.

In order to successfully complete the development of the DPRS transformer, accurate material properties verified by test and static / dynamic analysis technologies must be secured in advance. We were able to successfully secure the core technologies and verify the outcome through tests with the actual DPRS transformer.

Despite the amount of effort required, we believe the DPRS transformer is the technology much needed for future generations and hence chose to pursue the new innovative challenge. We are confident that the global demand for DPRS transformers will continue to grow with the ESG policies and people's rising interest in safety. We have successfully secured these core DPRS transformer technologies and eagerly look forward to our efforts contributing to the expansion of the electric machinery industry.

PEER REVIEWED

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Authors

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