Study on computation of optimal depth increase of embossed panels of stainless water tank for energy storage system

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Abstract
The objective of this study was to compute the optimal depth increase of the embossed panels of a stainless water tank used for an energy storage system. The pressing used to emboss the panels of the stainless water tank decreases their thickness. By assuming that the panels had the same volume before ($V_o$) and after the change ($V_c$), we found an equation that computed how much the thickness of the panels decreased. According to the obtained thickness equation, the thickness of arch-embossed panels decreased by 50% relative to flat panels, and that of pyramid-embossed panels decreased by up to 30%. We also performed finite element method analyses of four flat panels, four arch-embossed panels, and four pyramid-embossed panels by applying the thickness equation for different depth increase. As a result, the optimal depth increase of the arch-embossed panels was 70–90 mm, and that of the pyramid-embossed panels was 150–200 mm. We concluded that these computed optimal depth increase could be useful in the economic design of a stainless water tank for an energy storage system.

Keywords
Energy storage system, stainless water tank, arch-embossed panel, pyramid-embossed panel, volume conservation, optimal depth increase

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Introduction
The energy storage system market is in the initial stage of market formation, which is led by the United States, Japan, and other developed countries. Such systems are expected to play a fundamental role in converting the new renewable energy that is now actively being developed into high-quality power and connecting it to the electrical grid.¹ Currently, studies are being conducted on the capacities of energy systems that can use wind power generators² and the solar heating system with seasonal water tank heat storage to transfer the solar energy from summer to winter as shown in Figure 1.³ The purpose of this study was to compute the optimal depth increase of the embossed panels of a stainless water tank used to store eco-friendly electricity as thermal energy that could be used at any time.

Water tanks are an efficient method of storing eco-friendly, electrical energy as thermal energy for use in case of drought or an electric power shortage. Fiber-reinforced plastic (FRP), polyethylene double frame

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(PDF), and stainless steel (STS) panels are used to build such water tanks. STS is commonly used for a bulk water tank because of its strength, which is six times greater than that of FRP and 1.5 times greater than that of mild steel, as well as its easy sanitary control and resistance to rust.4 Figure 2 shows an STS304 water tank with embossed panels. The introduction of embossed panels to water tank is possible to reduce the stress and deflection due to the increased stiffness that flat ones for the same applied load and the increased stiffness can also decrease the material costs due to the reduced thickness of panels.

Figure 3 shows the cost fluctuations of steel plates and stainless plates (STS304 plates) and indicates that stainless plates are about 3.27 times more expensive than steel plates (average cost of steel plates: 1,150,000 won/tonf and that of stainless plates (STS304 plates): 3,760,000 won/tonf). Thus, it is imperative to study ways to reduce the high cost of the stainless plates used for an STS304 water tank while maximizing their strengths.

According to a recent study,5 the bending and shear stresses that occur in water tanks are governed by the water pressure. Because the thickness of a water tank is mostly determined by the bending stress, STS304 water tanks are manufactured with stainless flat panels, as shown in Figure 4(a) or arch-embossed panels, as shown in Figure 4(b). A load of about 40 and 80 ton is applied to form the embossing to stainless flat panels by typical rolling mill with load reduction ratio of 4%–7% and a low speed of 20 to 30 m/min. As shown in Figure 4(c), inner connection part is bent at 90° and outer connection part is bent at 45° to form the junction of the panels, and Figure 4(d) is the completed water tank with arch-embossed panels. Although the bending moment, shear force, and axial force act on the cross section of such arch-shaped structures, as they do on the cross section of flat structures, their horizontal reaction remarkably reduces the bending moment caused by the vertical loads. This shows that an arch-shaped structure is the right candidate for structures governed by vertical loads.6

Major research has been focused on the STS in workability and surface finishing to enhance the usability of STS.4,7,8 However, few studies have considered the optimal depth increase of arch-shaped panels, which could reduce the cost of materials when reforming flat panels into embossed panels. Because there is no clear method to compute the depth increase of panels, the thicknesses of the panels are determined using only field experience. If the optimal depth increase of the panels could be calculated, we could determine the optimal thickness for panels that are resistant to water pressure, and the thickness of the expensive stainless panels used for a water tank could be designed to have the optimal cross-sectional area, which would save material cost.

Thus, the objective of this study was to suggest a method to compute the optimal depth increase by...
finding an equation for the thickness of the embossed panels based on the assumption of volume conservation when pressing a STS panel and thus reducing its thickness. In addition, a finite element method (FEM) analysis was used to analyze the deflection of an elastic section.

Methods of analysis

Panel data

STS304 panels\(^9\) were used for this study. As listed in Table 1, each panel was either flat or embossed with an arch or pyramid shape, with four different panel thicknesses tested.

Each panel was 1m × 1m in size, which is the most frequently used size. Because 25 mm of each edge was bent over, as shown in Figure 4(c), the STS304 panels in Figure 5(a) and (b), which were used for the structural analysis, were squares with 950 mm sides. The radius (r) of the arch-embossed part was 450 mm, and the pyramid-embossed panels had a horizontal length (L/2) of 450 mm from the starting side of bending to the center of the panel. The width of the area that was not embossed (C) was 25 mm. For every type of panel listed in Table 1, thicknesses (t\(_o\)) of 1.5, 2.0, 2.5, and 3.0 mm was used. The thickness after pressing is denoted as \(t_c\) and the depth increase of the arch and pyramid panels is described as \(d_i\) in Figure 5. Both-end-hinge boundary conditions were used for the
panels because of the L shape caused by the inside panel point welding.

**Structural analysis modeling**

The bent panels comprised two types: arch-embossed panels in Figure 6(a) and pyramid-embossed panels in Figure 6(b). In the three-dimensional modeling, the panels were assumed to be isotropic, elastic, and homogenous. Four-node shell elements were used, with 424 shell elements used for the arch-embossed panels and 164 used for the pyramid-embossed panels.

Based on the result of the patch test as shown in Figure 10, the width \((b)\) and length \((a)\) of the arch-embossed panels were 11 and 7 cm, respectively, with a maximum width-to-length ratio \((b/a)\) of 1.57. The pyramid-embossed panels were modeled with widths and lengths of 10 cm and a maximum width-to-length ratio of 1.0.\(^{10}\) The weight on the surface of the panels was 10 kN/m\(^2\). The junction of the bent panels is welded to the end of the bent part and is reinforced by an L-shaped frame inside water tank. Therefore, the restraint on the rotation at the junction does not substantially exist. Both-end-hinge boundary conditions were applied to the edge of each side\(^{11,12}\) as shown in Figure 6.

**Formulation process**

When pressing to form the embossing in the flat panels, we assumed that the thickness of the cross section governed by pressing is reduced in the same manner. In addition, although pressing on the panels decreased the

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**Table 1. Material properties of STS304 panels.**

| Shape  | Name | Spec | \(t_e\)(mm) | \(f_y\)(MPa) | \(f_u\)(MPa) | \(E\)(MPa) |
|--------|------|------|-------------|-------------|-------------|------------|
| Flat   | F1.5 | STS304 | 1.5         | 280         | 640         | 193,000    |
|        | F2.0 | STS304 | 2.0         | 280         | 640         | 193,000    |
|        | F2.5 | STS304 | 2.5         | 280         | 640         | 193,000    |
|        | F3.0 | STS304 | 3.0         | 280         | 640         | 193,000    |
| Arch   | A1.5 | STS304 | 1.5         | 280         | 640         | 193,000    |
|        | A2.0 | STS304 | 2.0         | 280         | 640         | 193,000    |
|        | A2.5 | STS304 | 2.5         | 280         | 640         | 193,000    |
|        | A3.0 | STS304 | 3.0         | 280         | 640         | 193,000    |
| Pyramid| P1.5 | STS304 | 1.5         | 280         | 640         | 193,000    |
|        | P2.0 | STS304 | 2.0         | 280         | 640         | 193,000    |
|        | P2.5 | STS304 | 2.5         | 280         | 640         | 193,000    |
|        | P3.0 | STS304 | 3.0         | 280         | 640         | 193,000    |

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**Figure 5.** Geometric properties of STS304 panels for analysis: (a) arch-embossed panel and (b) pyramid-embossed panel.

**Figure 6.** Structural analysis modeling of STS304 panels: (a) arch-embossed panel and (b) pyramid-embossed panel.
thickness of the embossed parts, we assumed that the initial volume \( V_o \) and final volume \( V_c \) were the same to find an equation for the thicknesses of the arch-embossed panels and pyramid-embossed panels.

**Arch-embossed panels**

In order to determine the change in the thickness of an arch-embossed panel, the radius of the depth increase \( r \) was calculated using the depth increase \( d_i \) and radius of the panel surface \( r_0 \) based on the geometric conditions shown in Figure 7(b) and equation (1). The surface area with the deviant crease line \( S \) in Figure 7(a), excluding the base side of the arch-embossed panel’s surface, can be described by equation (2). Equation (2) can also be described as equation (3) to compute the surface area \( S \) from equation (3) multiplied by the panel’s changed thickness \( t_c \) is equal to the flat panel’s surface area \( \pi r_0^2 \) multiplied by the initial thickness \( t_o \).

Thus, by rearranging equations (1), (3), and (4), we can obtain equation (5), which computes the changed thickness of the panel \( t_c \).

\[
r = \frac{(r_0^2 + d_i^2)}{2d_i} \quad (1)
\]

\[
S = \int_0^{2\pi} \int_0^r r^2 \sin \phi d\phi dr \quad (2)
\]

\[
S = 2\pi r^2 \left( -\frac{r + d_i}{r} + 1 \right) \quad (3)
\]

\[
S \cdot t_c = \pi \cdot r_0^2 \cdot t_o \quad (4)
\]

\[
t_c = \left( \frac{r_0^2}{r_0^2 + d_i^2} \right) t_o \quad (5)
\]

**Pyramid-embossed panels**

The diagonal length \( h_o \) of a pyramid-embossed panel can be described by equation (6), with the depth increase \( d_i \) and length of the base \( L \) based on the geometric conditions shown in Figure 8. The surface area \( S \) of a bent pyramid panel without the base side can be described by equation (7). In addition, assuming volume conservation \( V_o = V_c \), the surface area \( S \) multiplied by the changed thickness \( t_c \) of the panel is equal to the surface area of the flat panel \( L^2 t_o \) multiplied by the initial thickness \( t_o \).

Thus, by rearranging equations (6), (7), and (8), we can obtain equation (9) to describe the changed thickness \( t_c \).

\[
h_o = \sqrt{d_i^2 + \left( \frac{L}{2} \right)^2} \quad (6)
\]

\[
S = L \cdot \sqrt{L^2 + 4d_i^2} \quad (7)
\]

\[
S \cdot t_c = L^2 \cdot t_o \quad (8)
\]

\[
t_c = \left( \frac{L^2}{\sqrt{L^2 + 4d_i^2}} \right) t_o \quad (9)
\]

Equations (5) and (9), thickness after the deformation by pressing using the law of conservation of volume, are formulated for finite element (FE) analysis to determine the optimal depth increase.

**Thickness ratio of panels**

Using equation (5), which describes the change in the thickness of an arch-embossed panel, we obtained Figure 9(a), which describes the relationship between the changed thickness \( t_c \) relative to the thickness of the flat panel \( t_o \) and the depth increase \( d_i \) relative to the radius \( r \). In addition, using equation (9), which describes the change in the thickness of a pyramid-embossed panel, we constructed Figure 9(b) to show the relationship between the changed thickness \( t_c \) relative to the thickness of the flat panel \( t_o \) and the depth increase \( d_i \) relative to the horizontal length \( L/2 \) from the starting side of the bending to the center of the pyramid-embossed panel. After analysis, Figure 9 shows that the thickness of an arch-embossed panel was decreased by up to 50% compared to the thickness.
of the flat panel, and that of a pyramid-embossed panel was decreased by up to 30%.

**Analysis results**

**Patch test**

In this study, the shell element shape was determined by checking the errors using a patch test for the reliability of the results from a three-dimensional structural analysis.

Arch-embossed panels with a depth increase ($d_i$) of 70 mm and thickness ($t_o$) of 2 mm were used for the patch test. Shell elements were modeled based on four-node and three-node elements, using 200, 424 and 1400 four-node elements and 222, 444 and 1403 three-node elements for the analysis. As a result, the average center deflection of the four-node models was 1.72 mm, with a standard deviation of 6% and coefficient of variation of 3% as shown in Figure 10(a). The average center deflection of the three-node models was 1.63 mm, with the standard deviation and coefficient of variation being 10% and 6%, respectively, as shown in Figure 10(b). These results indicated that the four-node models, which had smaller error percentages, should be used with a three-dimensional FEM.

**Center deflection**

We performed the FEM analysis by applying the equation of the thickness change relative to the depth increase for 12 panels, which included the flat panels, arch-embossed panels, and pyramid-embossed panels with four different thicknesses. We also analyzed the center deflection of each of these 12 panels.

The arch embossing was modified because the entire embossed area was deflected vertically by the water pressure. Figure 11 shows the vertical center deflections relative to the depth increase of the arch-embossed panels according to the results of the analysis.
lowest point of the U-shaped curve distribution occurs for all the arch-embossed panels when the depth increase is 70–90 mm. As the thickness of the arch-embossed panels expands, the optimal depth increase expands horizontally. From A1.5 curve as shown in Figure 11, we know that initial deflection is reduced due to the arch action, but the thickness of the arch-embossed panels reduced by pressing gradually increases the deflection.

As for the pyramid-embossed panels, we analyzed the deflection of the apex of the pyramid and center of each side, which formed a triangle. The maximum deflection occurred at the center of the triangle. The deflection at the apex of the pyramid formed by four triangles is smaller than the deflection at the center of the triangles by the restraint action of the boundary of the triangles.

Figure 12(a) shows the vertical deflection of the apex of the pyramid-embossed panels relative to the depth increase. The lowest point of the gradual U-shaped curve distribution occurs on every pyramid-embossed panel, and as the thickness of the pyramid-embossed panels expands, and the optimal depth increase expands horizontally.

Figure 12(b) shows the vertical deflections at the centers of the triangles of the pyramid-embossed panels relative to their depth increase. As the depth increase reaches 130 mm vertically, the deflection increases and then decreases until the depth increase reaches 150 mm. After 150 mm, the deflection increases again in the form of the curve distribution. This phenomenon usually occurs at low arches, and when the depth increase is less than 150 mm, the pyramid-embossed panels experience the snap-through phenomenon, which causes the nonlinear deflection to increase.15 Thus, considering the snap-through, we need to change the depth increase by 150–200 mm for the pyramid-embossed panels, as shown in Figure 12(b).

Table 2 lists the analysis results for the 12 panels. In the case of the flat panels that do not have depth increase, as the thickness increases, the deflection decreases, and out of the four flat panels, the maximum deflection (554 mm) occurs at a thickness of 1.5 mm. As for the arch-embossed panels, the center deflection and maximum deflection are equal. As for the pyramid-embossed panels, the center deflection and maximum

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**Figure 11.** Depth increase versus center deflection graph of arch-embossed panel.

**Figure 12.** Depth increase versus deflection graph of pyramid-embossed panel: (a) depth increase versus center deflection and (b) depth increase versus maximum deflection.
deflection occur at different places. Although the center deflection is about half that of the arch-embossed panels, the maximum deflection at the center of the triangular side is about three times greater. Using these deflection values, we evaluated the optimal depth increase of the arch-embossed panels and pyramid-embossed panels ($d_{i, eff}$).

**Optimal depth increase**

Figure 13 shows the results for the optimal depth increase according to the thickness of the panel. The optimal depth increase was calculated using the depth increase and deflections at the center points. As a result, the optimal depth increase of the arch-embossed panels was 70–90 mm, and that of the pyramid-embossed panels was 150–200 mm. It was also shown that as the thickness increased, the optimal depth increase increased.

**Conclusion**

The objective of this study was to determine the optimal depth increase of embossed panels for a stainless water tank used as an energy storage system. We found the equations for the thicknesses of arch-embossed panels and pyramid-embossed panels by assuming volume conservation while considering how the thickness

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**Table 2. Analysis results.**

| Shape | Name  | $t_o$(mm) | $t_r$(mm) | $d_{i, eff}$(mm) | $\delta$(mm) |
|-------|-------|-----------|-----------|------------------|--------------|
| Flat  | A1.5  | 1.5       | 0.976     | 70               | 3.87         |
|       | A2.0  | 2.0       | 1.952     | 70               | 1.71         |
|       | A2.5  | 2.5       | 2.423     | 80               | 0.92         |
|       | A3.0  | 3.0       | 2.883     | 90               | 0.55         |
| Arch  | P1.5  | 1.5       | 0.697     | 150              | 1.81         |
|       | P2.0  | 2.0       | 0.797     | 170              | 0.84         |
|       | P2.5  | 2.5       | 0.931     | 190              | 0.47         |
|       | P3.0  | 3.0       | 1.080     | 200              | 0.38         |

**Figure 13.** Optimal depth increase versus thickness: (a) arch-embossed panel and (b) pyramid-embossed panel.
of an embossed panel decreased during the process of pressing. We used the FEM to analyze the deflection at the elastic sections of 12 different types of panels and determined the optimal depth increase. As a result, the optimal depth increase of the arch-embossed panels was found to be 70–90 mm, and that of the pyramid-embossed panels was 150–200 mm.

It is difficult to induce the theoretical deflection formula of the embossed panels. For this reason, it presents only the process and the optimal depth increase of STS304 panels with $1m \times 1m$ in size through the FEM analysis. We suggest that future studies should derive theoretical deflection formula of stainless panels that can be useful in the field and include corrections for material nonlinearities.

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References
1. Clayton TC, Donald FE and John AR. Engineering fluid mechanics. New York: Wiley, 2002, pp.15–60.
2. Heo JM, Kim HK and Kim JS. The finite element analysis of shell structures using improved shell element. J Korea Soc Comput Struct 2000; 13: 449–460.
3. Hausild P, Pilvin P and Karlrik M. Mechanical behavior of a metastable austenitic stainless steel. In: ESOMAT, 2009. 06016, http://www.esomat.org/articles/esomat/pdf/2009/01/esomat2009_06016.pdf
4. Hibbeler RC. Structural analysis SI. Upper Saddle River, NJ: Pearson, 2009, pp.61–102.
5. Jang SP, Kim MY and Kim SP. Elastic stability. Seoul, South Korea: Seoul National University Press, 1999, pp.52–120 (in Korean).
6. Joo JW, Kim MK and Kang SI. Structural analysis of externally reinforced FRP water tank. J Inst Construct Technol 2011; 30: 115–123.
7. Kang MS, Jin KM, Kim EH, et al. A study on the determining ESS capacity for stabilizing power output of Haeng-won wind farm in Jeju. J Korean Sol Energ Soc 2012; 32: 25–31.
8. Kern WF and Bland JR. Solid mensuration with proofs. 2nd ed. New York: Wiley, 1948, pp.50–406.
9. Kim SK, Cho Y-T and Jung Y-G. Determination of efficient superfinishing conditions for mirror surface finishing of stainless steel. J Korean Soc Manuf Process Eng 2013; 12: 99–105.
10. Kim YS, Park JG, Ahn DC, et al. Review of formability and forming property for stainless steel. Trans Mater Process 2011; 20: 193–205.
11. Korea Institute of Steel Construction. Steel structure design criteria. Seoul, South Korea: Goomibook, 2007, pp.82–150 (in Korean).
12. Lee BK, Kim SK and Lee TE. Application of numerical differentiation in structural analyses of arch structures. J Korea Soc Comput Struct 2006; 19: 441–447.
13. Ma SS. ESS supply business model and roadmap plan. J Electr World/Month Mag 2012; 431: 33–43.
14. Petit N and Rouchon P. Dynamics and solutions to some control problems for water- tank systems. IEEE T Automat Contr 2002; 47: 594–609.
15. Sun D, Xu J and Ding P. Performance analysis and application of three different computational methods for solar heating system with seasonal water tank heat storage. Adv Mech Eng 2013; 2013: Article ID 857941 (13 pp.).