JURNAL LOCUS: Penelitian & Pengabdian
Volume 5 No. 6 June 2026
E-ISSN 2829-7334| P-ISSN 2829-5439
Hompage: https://locus.rivierapublishing.id/index.php/jl

Static Analysis and Experimental Validation of Containerized Fire Pump Stations

Firmansah, Adyana, T. Ardiansyah
Institut Sains Dan Teknologi Nasional, Indonesia
Email: syachf@gmail.com

Keywords:
Containerized fire pump station; NFPA 20; FEA; validation; stacking

Abstract

Containerized fire pump stations repurpose ISO 40ft High Cube containers but require large openings for ventilation and access, altering structural stiffness. his study evaluates a modified container under three load cases: LC2 (dynamic lifting, 1.2g), LC3 (static operation), and LC4 (2-tier stacking, 1.8g). A mesh convergence study established a reference mesh with maximum element size h = 20 mm. Validation was performed by comparing incremental deflections (Δδ) at six measurement points (T1–T6) between FEA and a workshop static test under LC3, using Mean Absolute Percentage Error (MAPE) as the accuracy metric. The validated model achieved a global MAPE (T1–T4) of 10.01%, indicating adequate agreement in global stiffness. For the reference mesh, key results are: LC3 – σvm,max = 161.56 MPa, δmax = 2.69 mm, SFdesign,min = 1.55; LC2 – σvm,max = 236.71 MPa, δmax = 3.40 mm, SFdesign,min = 1.14; LC4 – σvm,max = 296.21 MPa, δmax = 2.86 mm, SFdesign,min = 1.16. Stress hotspots are localized around openings, showing indications of spot stress/singularity; therefore, structural interpretation focuses on global response and nominal stresses in primary load-carrying members. The integration of NFPA 20 ventilation and access requirements with ISO 1496-1-based structural assessment is feasible using a validated FEA model. The modified container meets yield and deflection limits, providing defensible operational limits for lifting and 2-tier stacking under controlled dynamic factors.

INTRODUCTION

The use of ISO containers as engineering modules has grown rapidly in the last two decades. ISO 40 ft High Cube containers, which were originally designed as a cargo transportation medium in the global logistics chain, are now widely re-purposed into accommodation rooms, equipment modules, panel rooms, generator containers, and fire pump stations (Ataei, 2019; Indonesian Classification Bureau, 2018; Blanford & Bender, 2020; Chawa & Mukkamala, 2018).

In large-scale industrial facilities, fire pump stations act as the heart of water-based fire protection systems (Ekunke et al., 2024; Farrell et al., 2023; Yusoff et al., 2020). Failure of the fire pump at the time of a fire incident has the potential to render the entire layer of active protection ineffective (Chawa, P. K., & Mukkamala, 2018; Foster, 2019). Conventionally, fire pump stations are placed in buildings permanent concrete or steel. However, for projects in remote locations, with tight construction schedules and high flexibility requirements (e.g. future relocation or capacity expansion needs), containerized fire pump station solutions are becoming increasingly attractive. In this approach, the pump, propulsion engine (diesel or electric motor), control panel, pipe manifold, fuel tank, and other auxiliary equipment are installed inside a single modified ISO 40 ft High Cube container unit.

In this thesis, the abbreviations are: fire pump station (FPS), finite element analysis (FEA), and center of gravity (CoG). Absolute deflection is expressed by δ, while incremental deflection due to additional load is expressed by $\Delta\delta$. The load cases analyzed include LC2 (lifting), LC3 (operation in the foundation/static test workshop), and LC4 (stacking).

Furthermore, NFPA 20 sets out the requirements that pump chambers must meet, including ventilation, access to maintenance, and equipment layout (Chawa & Mukkamala, 2018; National Fire Protection Association, 2019). To meet these requirements in the container, manufacturers generally add large intake and exhaust louvers, wide double doors, and install an internal baseframe to distribute the load of equipment to the container structure. These modifications make the modified container geometry significantly different from the manufacturer's standard design, especially in the area of the corrugated panel and the frame around the opening (Ataei, 2019; Blanford & Bender, 2020; Chawa & Mukkamala, 2018; Giriunas, Sezen, & Dupaix, 2012; International Organization for Standardization, 2013)

Structurally, containers can be viewed as a space frame system with the contribution of corrugated panels (walls and roofs) to the shear rigidity of the in-plane (Yu & Chen, 2018). The main components such as corner fittings, corner posts, top side rails, bottom side rails, end frames, floor cross members, as well as corrugated wall and roof panels form a typical load flow path (Foster, 2019; Ataei, 2019; Giriunas, Sezen, & Dupaix, 2012; International Organization for Standardization, 2013). Corner fittings and corner posts bear the vertical compressive force due to stacking, the side rails and end frames bear the bending and racking forces, while the corrugated panels act as sliding diaphragms that add in-plane rigidity to the walls and roof (National Fire Protection Association, 2019; Oterkus et al., 2022).

The ISO 40 ft High Cube container has a frame structure system consisting of corner fittings and corner posts at the four corners, top side rail and bottom side rail along the longitudinal side, end frame at both ends, as well as floor cross members and corrugated panels on the walls and roof, which collectively form vertical load flow lines as well as racking as the basis for evaluating structural capacity (Yildiz, 2019). In the context of a fire pump station, the provisions for ventilation, access, and room temperature control as required in NFPA 20 require significant openings in the container walls for the intake and exhaust louvers as well as wide access doors. This modification raises design conflicts because cutting wall plates has the potential to lower global rigidity and alter the force distribution of the main frame, as reported in various studies of container utilization as building structures and special applications (Pinilla-Melo et al., 2025; Rzeczycki & Wiśnicki, 2016).

The design of the unit studied uses two intake louvers measuring 800 × 1300 mm on the front side at high level, two passive exhaust louvers measuring 900 × 2000 mm on the rear side (end wall high level), one double door on the side for operational access, and a rigid frame (stiffener) around the opening connected to the main frame. Inside the container are placed the main equipment such as diesel fire pump, electric fire pump, jockey pump, fuel tank, control panel, as well as suction and discharge pipe manifolds attached to the internal baseframe. Observations on the unit suggest that the area around the double door has the potential to undergo local deformation when the container is treated like a standard container and stacked in multiple layers, indicating that the effect of wall modification on structural response has not been fully accommodated in the initial design and that the stacking or shipping scenario needs to be re-analyzed taking into account geometric changes.

In addition to ventilation and access aspects, the configuration of lifting and handling logistics is also a crucial factor in the structural evaluation. The position of the lifting point on the top corner fitting, the location of the center of gravity (CoG), and the configuration of the lifting arrangement using a spreader greatly affect the force distribution of the corner fitting and the main frame. Therefore, the definition of load case lifting (LC2) in the FEA analysis must explicitly consider the CoG position and the rigging scheme used so that the calculated voltage and deflection responses represent actual conditions in the field, especially in modified units with internal mass distributions that are no longer identical to standard empty containers.

The modification of the ISO 40 ft High Cube container into a containerized fire pump station raises the need for more specific structural verification due to changes in geometry and load path, such as the addition of double doors, ventilation louvers, ladder access, opening stiffeners, and the placement of internal equipment that have the potential to affect the overall strength and rigidity of the structure. Modified containers must still meet operational demands under static operating conditions above the foundation/workshop (LC3), lifting/hoisting during lifting (LC2), and stacking during stacking (LC4), without exceeding the material melting limit or causing permanent deformation that interferes with corner fitting function and ISO compatibility. This study formulates problems related to von Mises equivalent voltage response (σvm), global deflection (δ), and design safety factor (SFdesign), as well as evaluates the reliability of the 3D solid FEA numerical model through a verification-validation process, including mesh convergence studies, boundary condition and contact control, as well as experimental validation based on workshop static tests with relative error metrics and MAPE. The security factor is defined as SFdesign = $f_{d,i}/\sigma vm$ with $f_{d,i} = f_{y,i}/\gamma M$, while SFyield = $f_{y,i}/\sigma vm$ is used as a reference; Eligibility decisions are based on those definitions, not solely on the software's built-in contours.

This study aims to develop an accountable and experimentally validated 3D solid body FEA model, evaluate the performance of structures in LC2–LC4 using σvm, δ, and SFdesign parameters, identify the location of dominant hotspots in the opening and confess areas, and develop recommendations for lifting/stacking or derating capacity operational limits based on defensible evaluation results. The analysis was limited to a single unit of modified containers assuming isotropic linear elastic materials and small deformations, representation of dynamic effects as equivalent static loads, and modeling of joints as bonded contacts, without discussing nonlinear materials/geometry, buckling, fatigue, or weld damage. Overall, the study is significant because it provides a quantitative evaluation framework based on FEA integration and experimental proof, mapping critical zones along with the interpretation limits of the potential for spot stress/singularity, as well as producing a more measurable technical basis for the design and operation of fire pump station container decisions. This research provides a validated FEA framework for modified ISO containers, establishes defensible operational limits for lifting and 2-tier stacking, and demonstrates that NFPA 20 requirements can be quantitatively reconciled with ISO 1496-1 structural criteria. The findings offer practical guidance for manufacturers, operators, and certification bodies in designing and handling containerized fire pump stations.

RESEARCH METHODS

1. Types of Research

This research was quantitative research based on numerical and experimental analysis, which combines the three-dimensional solid body Finite Element Analysis (FEA) approach with static tests in the workshop. The quantitative approach was chosen because the focus of the study was to quantitatively measure the structural response in the form of Von Mises voltage, maximum deflection, safety factors, and global rigidity in a 40 ft High Cube ISO container modified into a fire pump station. Numerical analysis is used to simulate the behavior of structures in various critical load scenarios, while experimental testing is performed to verify the model's accuracy to real conditions. Characteristically, this research can also be categorized as engineering research with a verifiable approach. The FEA model does not stand alone as a theoretical simulation, but is validated through workshop static test data on the operating load case (LC3). Thus, this study is not only predictive, but also confirmative, as it compares the numerical response to the actual response of physical structures. This approach is important considering that modified container structures have geometric discontinuities (openings, confessors, joints) that are difficult to analyze using conventional manual calculations.

2. Population and Sample

The population in this study is the entire structural configuration of the ISO 40 ft High Cube container which is modified into a fire pump station system with a variety of operational loads, including lifting conditions, operation on the foundation, and multi-tier stacking. The population includes all possible structural responses due to a combination of modified geometry (louver openings, double doors, perimeter stiffeners, internal base frames) and variations of dynamic factors according to applicable technical standards.

The research sample is a unit of ISO 40 ft High Cube container that has been actually modified into a fire pump station and tested in a workshop. Numerically, the sample is represented in a 3D solid body FEA model with material properties assumed to be isotropic linear elastic. In the test aspect, samples were tested using a phased loading configuration up to 100% of the operational load (LC3), with deflection measurements at six reference points (T1–T6). With this approach, the physical sample and the numerical sample represent each other so that the results of the analysis can be directly related to the behavior of the actual structure.

3. Data Collection Techniques

The data collection technique in this study was carried out through two main methods, namely numerical data collection and experimental data collection. Numerical data were obtained through FEA modeling using element software up to a three-dimensional solid body approach. The data collected included the maximum Von Mises voltage distribution, maximum deflection, safety factors (SFyield and SFdesign), as well as structural responses on three main load cases (LC2 lifting, LC3 static workshop, and LC4 stacking 2-tier). In addition, mesh convergence studies were conducted to ensure the stability of the numerical response to the variation in element size.

Experimental data were collected through a static test workshop on the LC3 configuration. The test was conducted with a staggered load (0%–100%) using a dummy load that represents the actual operational load. Deflection was measured using a dial gauge at six measurement points (T1–T6) selected to represent the global and local response of the structure. The data obtained was in the form of incremental deflection at each stage of loading, which was then used to calculate relative error and Mean Absolute Percentage Error (MAPE) as the basis for numerical model validation.

4. Data Analysis Techniques

Data analysis was carried out quantitatively by comparing the FEA numerical results with the static test results to evaluate the global rigidity of the structure. The main parameters analyzed include maximum Von Mises voltage (σvm, max), maximum deflection (δmax), safety factor against yield (SFyield), design safety factor (SFdesign), and global deflection utilization ratio (URglobal). The strength evaluation was carried out by comparing the FEA result voltage to the allowable voltage ($fd = fy/\gamma M$), while the serviceability evaluation was carried out by comparing the deflection to the span ratio limit (L/480 or L/400 as a guide).

Model validation was carried out using the calculation of the Mean Absolute Percentage Error (MAPE) between the deflection of FEA and the deflection of the test results at the main global point (T1–T4). In addition, the global stiffness is calculated based on the slope of the load–deflection curve ($kglobal = \Delta F/\Delta\delta$) to ensure the consistency of the structure's elastic response. The mesh convergence study was also analyzed using relative errors between mesh levels to determine the optimum element size (h = 20 mm) as a compromise between accuracy and computational efficiency. With this analytical approach, the interpretation of the results rests not only on the value of the peak voltage sensitive to the local singularity, but also on the global response stability of the experimentally validated structure.

RESULTS AND DISCUSSION

LC3 Analysis Results: Operation in the Foundation (Static Workshop)

FEA results for LC3 are presented using a reference mesh h= 20 mm established through a convergence study in Chapter III. This section shows the contours of total deformation (deflection), Von Mises equivalent voltage, and safety factors to identify global responses and hotspot locations.

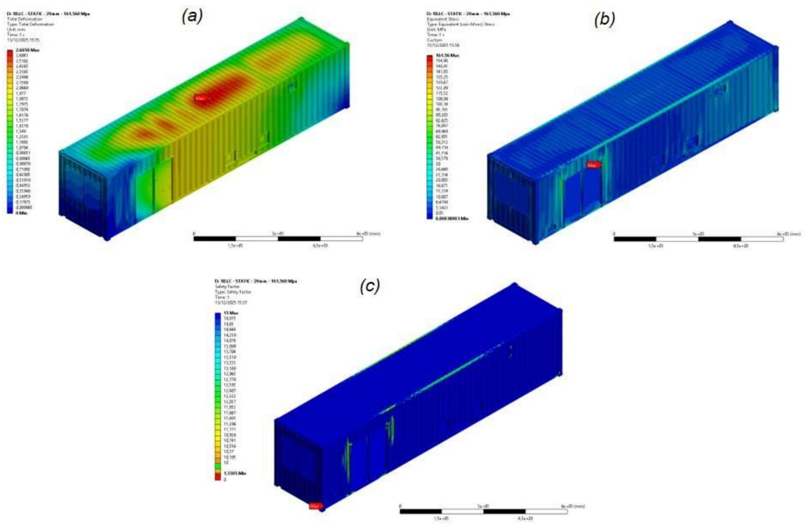

Figure 1. FEA LC3 (Static Workshop) results on reference mesh h= 20 mm: (a) total deformation, (b) Von Mises equivalent voltage, and (c) safety factor.
Source: Author's FEA analysis using ANSYS, 2025

The contour of the deformation in Figure 1(a) shows a global deflection response with the δmax location on the roof panel area of 2.69 mm. The maximum equivalent voltage, σvm,max, is localized on the wall panel of the double door area with a value of 161.56 MPa. The minimum design safety factor in the critical area is 1.55.

LC2 Analysis Results: Lifting (Dynamic Lifting - 1.2 g)

In the LC2 load case, the container is lifted through the top corner fitting using a crane. The modeled loads include self-weight and dummy loads, as well as dynamic lifting effects that represent crane acceleration, load swing, snatch load, and operation imperfections. In the FEA model, the lifting condition is represented by the lifting configuration of the top corner fitting according to the spreader scheme, while the rest of the structure is left to respond according to its rigidity.

The results of the LC2 analysis are presented using the h=20 mm reference mesh that has been established in Chapter III as a compromise between the stability of the global response and the need for computing resources. LC2 convergence studies showed that δmax was relatively stable when the mesh was compacted (3.15 rose to 3.40 and to 3.59 mm), while σmax increased significantly and in the voltage plot indicated a stress singularity. Therefore, the interpretation of LC2 results is focused on global response (deflection) and hotspot location identification, while the peak voltage value in the hotspot is treated as a sensitive spot stress to geometric details and mesh density.

Figure 4.2 shows the total deformation contour, Von Mises stress, and safety factors for LC2 using a 20 mm reference mesh. The maximum Von Mises voltage of σvm, max= 236.71 MPa is localized at the upper corner of the double door frame on the longitudinal side. Local voltage concentrations are also seen in some of the stiffener joint details around the opening. Meanwhile, the area of the corrugated panel on the central span of the sides/roof shows a lower voltage, which indicates the load flow path Lifting is dominant through the container frame system, and the maximum hotspot is affected by the local details of the opening/softener.

The contour of the total deformation shows a global response with δmax= 3,401 mm located in the roof panel around the mid span (the central area of the container roof). In the contour of the design safety factor, SFdesign was obtained, min= 1.1373. These minimums appear locally in hotspot areas around the spot area, while most structures are on a higher design safety factor. Given the singularity indication in the voltage plot, the values σvm, max and SFdesign, min at the hotspot is interpreted as spot stress; The evaluation of the feasibility of LC2 structures for linear elastic design is carried out primarily based on the global response as well as the nominal stress around the associated frame elements, rather than precisely at a singular point.

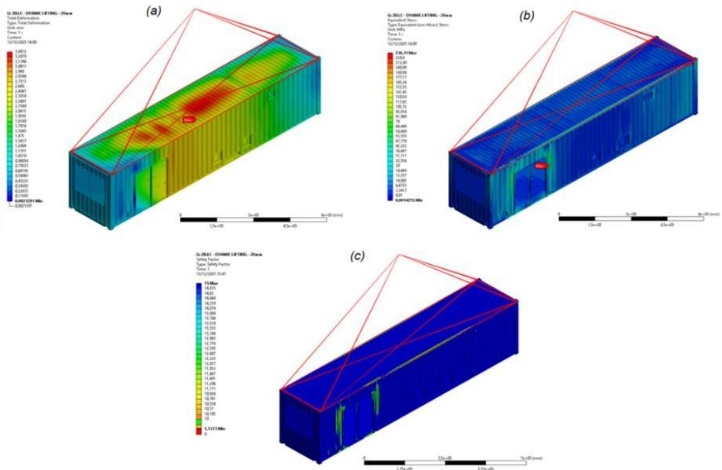

Figure 2. Total deformation contour, Von Mises voltage, and safety factor in LC2 (dynamic lifting) using a reference mesh h = 20 mm. Hotspot σvm,max is localized at the top corner of the double door opening
Source: Author's FEA analysis using ANSYS, 2025

A summary of the main values of LC2 results on the reference mesh is shown in Table 4.3.

Table 1. Summary of LC2 (dynamic lifting-1.2 g) results on reference mesh h= 20 mm

Parameter	Value	Units	Location records/descriptions
σvm,max	236,710	MPa	Local hotspots in the upper corner of the double door frame; Indications of the Singularity
δmax	3,401	mm	Global response; Maximum location on the roof panel around midspan (20 mm mesh deformation)
SFdesign,min	1,1373	-	Local minimum (spot) around the opening/stiffening details

Source: Author's compilation from FEA results, 2025

Taking these results into account, the global response of LC2 is on the order of millimeters and the voltage hotspots are localized to the aperture details. The LC2 model with reference mesh was considered adequate for linear elastic evaluation and was used as the basis for the next load case discussion.

LC4 Analysis Results: Stacking and Derating

In the LC4 load case, the container is evaluated at the stacking condition to represent the vertical compressive load transferred through corner casting due to container stacking. In this study, a 2-tier dynamic stacking scenario was used, so that the stacking load represents a limited stacking condition (e.g. storage/handling) and not a multi-tier maximum stacking condition. The configuration of boundary conditions and loads follows the LC4 definition in Chapter III.

The results of the LC4 analysis were presented using a reference mesh h = 20 mm. The mesh sensitivity study showed that the global deflection was relatively stable (δmax= 2.660 to 2.86 and to 3.06 mm), while the maximum voltage increased and in the voltage plot indicated a stress singularity in the hotspot area. Therefore, the interpretation of the LC4 results is focused on the global response (deflection) and stress distribution on the main frame elements around the stacking load path, while the peak value of the voltage at the hotspot is treated as a sensitive spot stress to the details of the geometry and density of the mesh.

Figure 4.5 shows the total deformation contour, Von Mises equivalent stress, and safety factor for LC4 on the reference mesh h= 20 mm. The contour of the deformation shows a global response with δmax= 2.86 mm. The maximum equivalent voltage in the reference mesh is σvm, max= 296.21 MPa and is local at the hotspot, so it is evaluated as spot stress. In the contours of the safety factor, SFdesign is obtained, min= 1.165, with the minimum zone being local to certain details, while most structures are at a higher design safety factor.

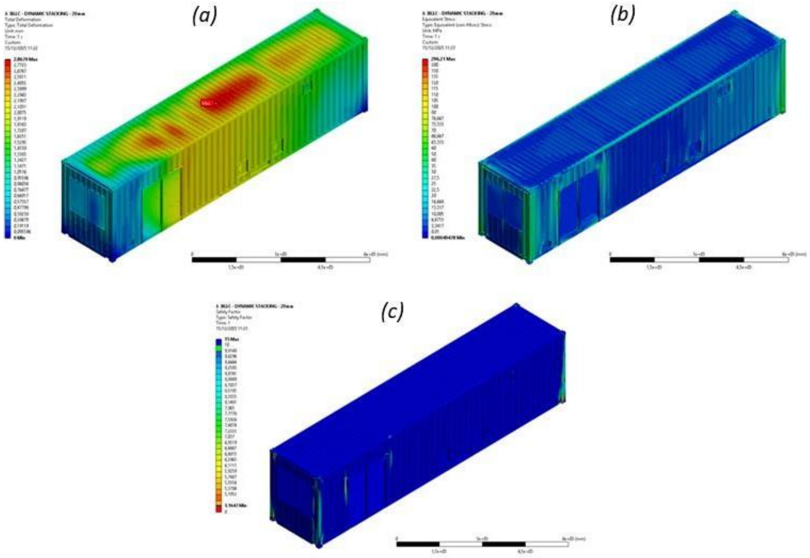

Figure 3. FEA LC4 (Dynamic Stacking - 2 Tier) results on the reference mesh h= 20 mm: (a) total deformation, (b) Von Mises equivalent voltage, and (c) design safety factors A
Source: Author's FEA analysis using ANSYS, 2025

A summary of the main values of LC4 results on the reference mesh is presented in Table 2.

Table 2. Summary of LC4 (Dynamic Stacking - 2 Tier) main results on the mold mesh h= 20 mm

Parameter	Value	Units	Location Notes/ Description
σvm,max	296,210	MPa	Local hotspots; Indicated Singularity (Spot Stress)
δmax	2,868	mm	Global response; Maximum location on the span panel length/roof of the contour of the deformation
SFdesign,min	1,165	-	Local minimum (spot) on certain details
Scenario Stacking	2	Tier	The stacking evaluation scenario is limited to this research/Thesis

Source: Author's compilation from FEA results, 2025

Based on these results, in the dynamic stacking scenario of 2 tier - 1.8 g the structure still shows a global response on the order of millimeters, but the minimum margin in the hotspot zone is relatively thin (SFdesign,min= 1.165) and is affected by local sensitivity (spot stress). Therefore, these LC4 results are declared adequate for the evaluation of linear elasticity in 2-tier limited stacking. If the container is planned for higher stacking, further analysis (e.g. nominal voltage definition, critical detail subtotaling, and more representative tier scenarios) is required before stacking/derating recommendations can be quantitatively determined.

Summary of LC2 - LC4 Analysis Results

This subchapter summarizes the main results of FEA analysis on LC2 (lifting), LC3 (operation in the foundation/static workshop), and LC4 (dynamic stacking 2 tier) using the reference mesh h= 20
mm. The parameters compared included the maximum Von Mises voltage σvm, max, maximum deflection δmax, minimum design safety factor SFdesign, min, as well as hotspot locations and notes related to singularity/spot stress indications.

Table 3. Summary of the main results of the FEA analysis for LC2-LC4 (reference mesh h= 20 mm)

Load Case	**σvm, max (MPa)**	**δmax (mm)**	**SF min ,design**	**Dominant hotspot locations**	**Notes singularity/Spot Stress**
LC2 - Dynamic Lifting	236,710	3,401	1,13	Top corner of the opening Double Door Frame	Indications of singularity on the plot voltage, local hotspot/spot stress (mesh sensitive)
LC3 - Static Workshop	161,560	2,695	1,55	Double door area wall panel (around frame/door header)	σvm, max is sensitive to local details; evaluation is focused on global response & voltage nominal around hotspot
LC4 - Dynamic Stacking (2 tier)	296,210	2,868	1,16	Frame path/corner post and local details around the opening	Indication of singularity on voltage plot ; SFmin, the design occurs locally (spot) on certain details

Source: Author's compilation from FEA results, 2025

Note: SFmin in this table is SFdesign = fd /σvm,max For reference to yield SFyield, SFyield ≈ γM · SFdesign
(γM = 1.5 → SFyield is about 1.5 times greater).

SFdesign, min occurs locally in hotspots indicated by spot stress/singularity; Feasibility evaluation is based not only on local peaks, but also global responses and nominal stresses in the truss line.

In terms of global response (deflection), all load cases show deformation on the order of millimeters. LC2 produces the largest maximum deflection, δmax=3.40 mm, which occurs on the roof panel around the midspan. Meanwhile, LC3 and LC4 produce maximum deflection that is still comparable on the same order, δmax=2.69 mm and δmax=2.86 mm, respectively. This deformation pattern is consistent with the character of the container structure which tends to exhibit a global response to the roof panel and the length span when receiving a combination of its own heavy load, equipment load, and lifting and stacking conditions.

In terms of hotspots and design/operation implications, LC2 is the most critical condition because it has σvm, max=236.71 Mpa and SFdesign, min=1.13, with hotspots localized in the door header/door frame. This underscores the importance of control of lifting operations to minimize dynamic loads (e.g. acceleration limiting, avoiding shock loads/snatch loads) and ensure fabrication quality, recognition details, and joints in the opening area.

In LC3, the minimum safety margin is still at SFdesign, min=1.55, and the validation results (Subchapter 4.3) show that the global rigidity of the model is in line with the test results, so that the LC3 results can be used as a basis for evaluating operational conditions in the foundation. At LC4 (dynamic stacking 2 tier 1.8 g), although $\sigma vm,max$ increases (296.21 MPa), the SFdesign,min value remains above 1 (about 1.16) so that limited stacking still shows an adequate design margin; However, hotspots are still local in certain details. For the sake of note, for the interpretation of the yield can be used ≈ $\gamma M \cdot$ SFdesign (e.g. γM=1.5).

Because some peak voltage values indicate singularity and are mesh sensitive, the interpretation of structural feasibility is focused on the global response (deflection) and nominal/representative stress on the main frame elements around the load path, rather than solely on the singular local peak point.

CONCLUSION

Based on a literature review, 3D solid FEA modeling, and workshop static test on a 40 ft High Cube ISO container modified into a containerized fire pump station, this study resulted in a validated solid 3D FEA model of the structure's global response. The reference mesh h = 20 mm was chosen as a compromise between response stability and computational efficiency, noting that the peak voltage in the hotspot area is locally sensitive (spot stress/singularity). Validation of the LC3 load case was carried out through an incremental deflection comparison between FEA and static assays at T1–T6 points, with a global MAPEglobal (T1–T4) of 10.01% which showed adequate suitability for elastic-linear evaluation. Under operating conditions in the foundation (LC3) $\sigma vm,max$ = 161.56 MPa, δmax
= 2.69 mm, and SFdesign, min = 1.42, while in lifting (LC2; 1.2g) $\sigma vm,max$ is obtained
= 236.71 MPa and SFyield = 1.46, and in 2-tier stacking (LC4) σvm, max = 296.21 MPa and SFyield = 1.16 (marginal but ≥ 1.0). In general, the container meets the criteria based on melting limits (SFyield ≥ 1.0), the global deflection is well below the serviceability limit of Lx/480 (URglobal 0.106–0.134), and meets the basic deflection tolerance according to ISO 1496-1:2013 ($\delta base \leq 6$ mm at 1.8R).

Thus, the modified containers meet the structural performance demands for stationary operation (LC3) and can be operated in 2-tier limited lifting and stacking conditions with dynamic load control and controlled operational limits. For further development, it is recommended to evaluate local voltage based on nominal voltage or sub-modeling in hotspot areas, add experimental validation using strain gauges in critical zones (door header/door frame and opening stiffener), and expand stacking studies on tier variations and dynamic factors to establish more quantitative stacking/derating limits. The integration of the ventilation needs of the fire pump system according to operational thermal standards also needs to be studied so that the modification of the opening maintains global rigidity and voltage margins, accompanied by an emphasis on lifting procedures that avoid shock loads as well as fabrication quality control and periodic inspections of critical areas.

REFERENCES

ANSYS Mechanical Academic Teaching Version. (2025). *License No. cc28aadbb66f, ISTN, Jakarta*.

Ataei, M. (2019). Design of a two-story ISO shipping container building (Master's project, Ryerson University, Department of Civil Engineering). Toronto Metropolitan University Research Repository.

Biro Klasifikasi Indonesia. (2018). *Guidelines for classification and construction – Part 6 statutory (Volume 8).*

Blanford, M., & Bender, S. (2020). Upcycling shipping containers for houses. *Cityscape: A Journal of Policy Development and Research, 22*(2), 95–100.

Chawa, P. K., & Mukkamala, S. K. (2018). Design and analysis of shipping container made of honeycomb sandwich panels. Blekinge Institute of Technology. https://doi.org/10.1016/S0924-0136(01)01034-2

Ekunke, O. V., Kehinde, T. O., Owunna, I. B., Ogunkanmi, S. A., Oyetunde, J. O., Dillum, M. N., & Adegoke, S. H. (2024). Innovations in fire detection and suppression systems for oil refinery operations. *Path of Science, 10*(11), 4001–4015.

Farrell, K., Hassan, M. K., Hossain, M. D., Ahmed, B., Rahnamayiezekavat, P., Douglas, G., & Saha, S. (2023). Water mist fire suppression systems for building and industrial applications: Issues and challenges. *Fire, 6*(2), 40.

Foster, T. (2019). NFPA 20: Fire pump design. *Consulting-Specifying Engineer*.

Giriunas, K., Sezen, H., & Dupaix, R. B. (2012). Evaluation, modeling, and analysis of shipping container building structures. *Engineering Structures, 43*, 48–57. https://doi.org/10.1016/j.engstruct.2012.05.001

International Organization for Standardization. (2013). *ISO 1496-1:2013: Series 1 freight containers – Specification and testing – Part 1: General cargo containers for general purposes*. ISO.

National Fire Protection Association. (2019). *NFPA 20: Standard for the installation of stationary pumps for fire protection (2019 ed.)*. NFPA.

Oterkus, S., Wang, B., Oterkus, E., Galadima, Y. K., Cocard, M., Mokas, S., Buckley, J., McCullough, C., Boruah, D., & Gilchrist, B. (2022). Structural integrity analysis of containers lost at sea using finite element method. *Sustainable Marine Structures, 4*(2), 11–27. https://doi.org/10.36956/sms.v4i2.505

Pinilla-Melo, J., Aira-Zunzunegui, J. R., La Ferla, G., de la Prida, D., & Navacerrada, M. Á. (2025). Design of a shipping container-based home: Structural, thermal, and acoustic conditioning. *Buildings, 15*(7), 3127. https://doi.org/10.3390/buildings15173127

Rzeczycki, A., & Wiśnicki, B. (2016). Strength analysis of shipping container floor with gooseneck tunnel under heavy cargo load. *Solid State Phenomena, 252*, 81–90. https://doi.org/10.4028/www.scientific.net/SSP.252.81

Yu, Y., & Chen, Z. (2018). Rigidity of corrugated plate sidewalls and its effect on the modular structural design. *Engineering Structures*, *175*, 191–200.

Yildiz, T. (2019). Design and analysis of a lightweight composite shipping container made of carbon fiber laminates. *Logistics, 3*(3), 18. https://doi.org/10.3390/logistics3030018

Yusoff, Y. F., Mohd-Lair, N. A., Tsen, M., & Harman, M. (2020). Case study on designing a comprehensive fire protection system for KY Power Station. *Journal of Physics: Conference Series, 1529*(3), 032098.