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LATERAL STIFFNESS EVALUATION OF RESIDENTIAL ISO CONTAINER MODULE: FULL-SCALED EXPERIMENTAL AND NUMERICAL STUDIES

Cher Siang Tan[a]*, Chie Hui Philip Ling[b], Yeong Huei Lee[c]

[a]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Ling & Wong Perunding Sdn. Bhd., 15, Jalan Permas 12/14, Bandar Baru Permas Jaya, 81750 Johor Bahru, Johor, Malaysia
[c]Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia

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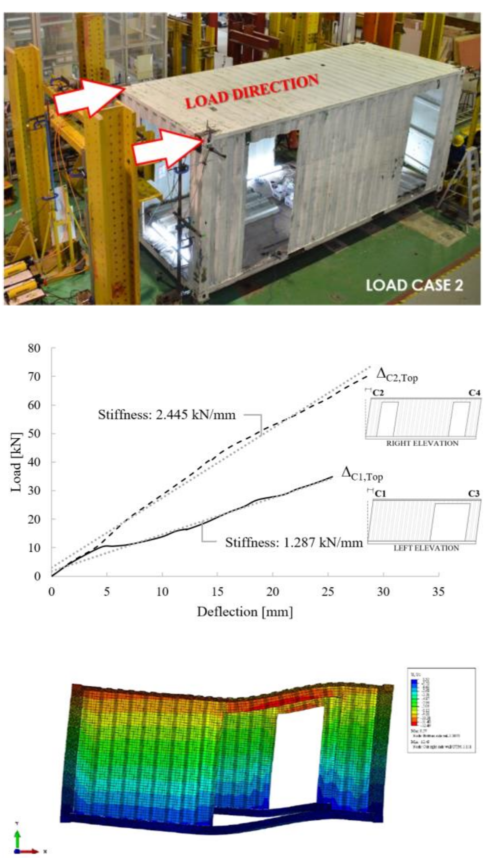
*Corresponding author
tcsiang@utm.my

Graphical abstract



Abstract

International Organisation for Standardisation (ISO) containers, designed to protect contents against extreme conditions, are often repurposed as temporary shelters during disasters, conflict, or urbanization. However, modifying these containers for housing greatly affects their structural integrity. Several studies have numerically and experimentally investigated the structural strength of container structures. However, there was limited information on the lateral stiffness of a residential ISO container subjected to lateral load. A piece of valuable information when the container is applied to a multi-story structure. This study proposed to conduct physical tests on two full-scaled residential ISO container structures to evaluate their lateral stiffness. Considering the actual condition of a residential container, both samples were fabricated with different sizes of openings. The finite element models of the samples were developed and analysed employing Abaqus for comparison with other studies and the experimental results. The application for lateral stiffness of ISO containers subjected to wind load was discussed based on the current design standard. The outcome of the study widened the scope of the structural behaviour of an ISO container towards the lateral stiffness of a residential container structure.

Keywords: ISO container, strength testing, lateral stiffness, finite element analysis, wall opening

Abstrak

International Organisation for Standardisation (ISO) kontena, direka untuk melindungi kandungan daripada keadaan ekstrem, sering kali diubah suai sebagai tempat perlindungan sementara semasa bencana, konflik, atau urbanisasi. Walau bagaimanapun, pengubahsuaian kontena boleh mengurangkan integriti struktur keseluruhannya. Pelbagai kajian telah menyelidiki kekuatan struktur kontena secara numerik dan eksperimen. Namun, terdapat maklumat pada kekakuan lateral seluruh struktur kontena kediaman apabila terdedah kepada beban lateral adalah terhad. Maklumat tersebut adalah penting apabila kontena digunakan untuk struktur berbilang tingkat. Kajian ini mencadangkan untuk menjalankan ujian fizikal pada dua struktur kontena kediaman ISO skala penuh untuk menilai kekakuan lateral mereka. Pelbagai saiz dan lokasi pembukaan telah diperkenalkan pada kedua-dua sampel kontena untuk mengambil kira keadaan sebenar. Model sampel kontena ISO tersebut telah direka dan dianalisis menggunakan aplikasi Abaqus untuk dibandingan dengan kajian hasil eksperimen. Hasil kajian ini telah memperluas skop tingkah laku struktur kontena ISO terhadap kekakuan lateral sebuah struktur kontena kediaman.

Kata kunci: Kontena ISO, ujian kekuatan, kekakuan lateral, analisis unsur terhingga, pembukaan dinding.

1.0 INTRODUCTION

The expected rise in global population to 9.7 billion by 2050 highlights urgent housing challenges, including a demand for affordable options and addressing the crisis for nearly one billion slum dwellers due to urban congestion and economic disparities [1-4]. Recently, container architecture showed its potential to mitigate the global housing supply issue as the concept of using the shipping container as a building was adopted by designers [5]. With its advantages of faster construction time and pre-fabrication ability, the container structure can become an option for engineers or architects as an alternative construction method [6]. Container buildings that were constructed can serve residential and commercial purposes [7].

Most freight container that is used today for cargo transportation follows the regularised ISO specification. The dimension, maximum cargo weight (known as rating), specification of the corner fitting for connection, and all the necessary markings had been standardised by regulations [8-10]. The inherent strength of an ISO freight container is also standardised following the ISO documentation with minimum loading and maximum deflection requirements for different load cases [11]. Nevertheless, the necessary opening required on the wall panel for ventilation and residential purposes in a container will depreciate its structural integrity [12]. This reduction in container capacity, especially its lateral stiffness is critical to be considered in engineering design as research has shown that the corrugated wall could contribute up to 95% of overall stiffness [13].

The investigation of the strength and stiffness of container structures began in the last two decades with numerical simulation of freight containers by using a space frame model [14]. Giriunas [15] performed a numerical study to simulate the stiffness of the container structure with the total removal of different wall panels. The stiffness of the container model was correlated to ISO specification by the introduction of a ratio based on minimum strength requirement. However, the work was not validated by experimental data. The outcome of the research was considered more conservative as the models were tested under linear or elastic limits. Besides, the total removal of walls was seldom done in temporary shelters as smaller apertures such as doors or windows were more common and practical. Furthermore, Zha and Zuo [16; 17] conducted theoretical, numerical and experimental testing on the ISO container which is the most comprehensive research work to date. The research proposes a calculation method of the container stiffness which was derived theoretically employing the energy method. However, the use of energy methods was tedious and not straightforward for engineering purposes. Besides their assumption on the frame-wall interaction had led to a very distinct difference between container stiffness near the load applied and stiffness far from the load which contradicts observations from other numerical predictions and physical tests. Moreover, their approach of stiffness reduction due to opening had not been validated with different opening configurations and panel orientations. Hence further investigation had to be carried out to verify the existing results. Although the stiffness of corrugated steel panels for roofing purposes has been thoroughly studied and documented [18], its application as a shear-resisting structure still requires more research.

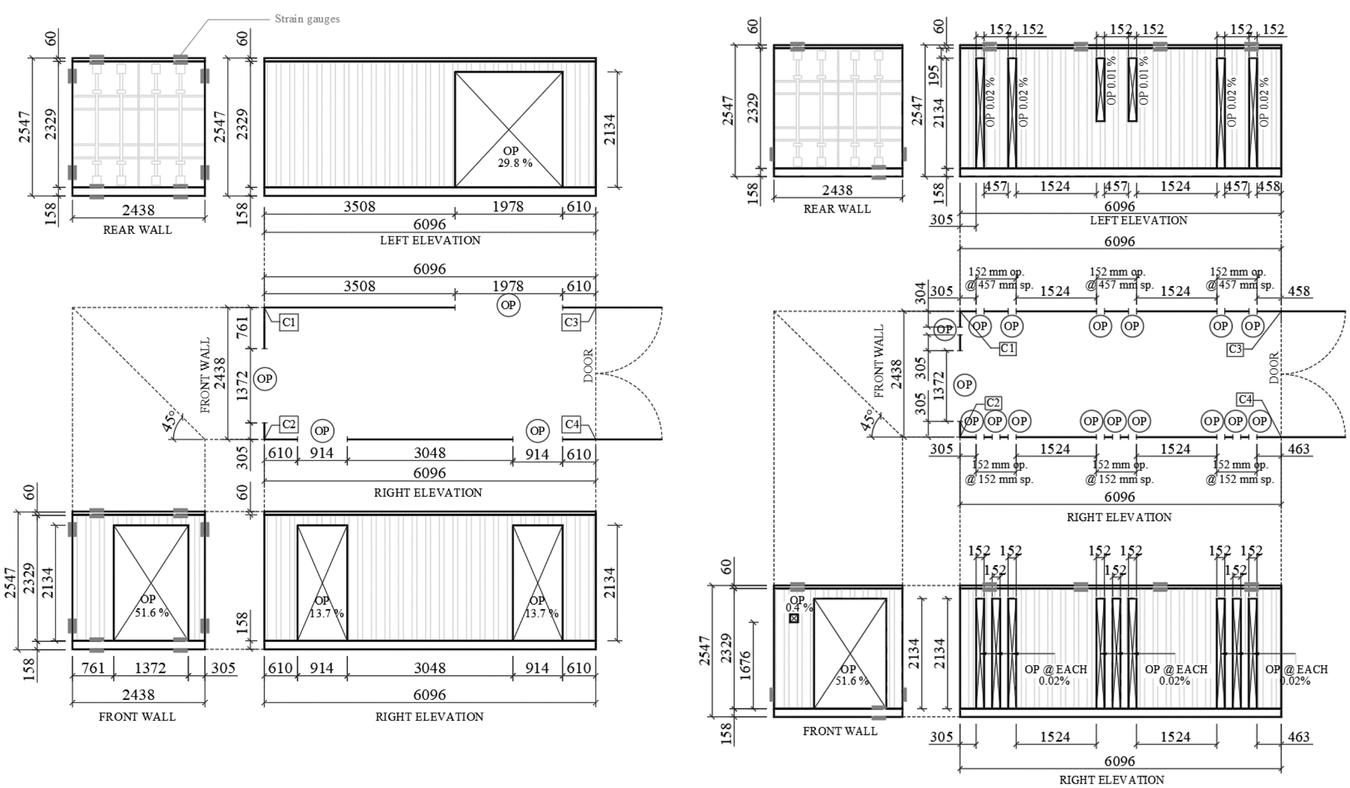
Research by T. Børvik *et al*. [19] and C. Genelin *et al*. [20] on the blast resistance of ISO containers revealed their capability to withstand high sudden loads, suggesting potential resilience against earthquakes or explosions. The studies highlighted the corner columns as critical structural elements during earthquakes. Furthermore, Sukhi V. *et al*. explored a mitigation strategy by optimizing the ductility and configuration of inter-modular connections to resist forces from external lateral motions, proposing a design that relocates failure points to more ductile components of the structure. However, a residential ISO container structure with openings required for living comfort subjected to lateral loading has yet to be investigated. Therefore, the structural behaviour and the stiffness of a residential ISO container subjected to lateral load should be investigated since they benefit the development of the rehabilitation shelter module.

This research aims to study the structural response of the residential ISO container structures with various wall openings under the effect of monotonic lateral load following BS ISO 1496-1 [11]. The lateral stiffness of the container was investigated by conducting a full-scaled physical load testing which included two ISO container samples followed by their numerical model analysis. A finite element model of the ISO container was proposed in the numerical study to simulate its structural response with different wall openings and the stiffness of container structures was also evaluated.

2.0 METHODOLOGY

2.1 Experimental Study

In this study, two twenty-feet reused ISO containers SC1 and SC2 with different opening configurations at the wall panel were proposed and fabricated for physical testing. The concept of container SC1 was designed so that to fulfil the requirements of a typical residential structure. It features large openings for windows and doors, allowing natural light and air to enter and create a comfortable living environment. On the other hand, the openings proposed in SC2 were smaller than in SC1 to provide sufficient air circulation in the container. The proposed container SC2 was believed to be practical to be applied in emergencies since it would be difficult to source window, and door frames during disasters. The layout and details of container SC1 and container SC2 prepared for the load test with dimensions like openings (op.), spacings (sp.), and corners (C1 to C4) were labelled accordingly and the location of strain gauges was shown in Figure 1. Further technical detail of components of an ISO container structure was thoroughly explained by Ling and Tan *et al*. [21]. The instrumentation setup is shown in Figure 2. Load cells were used to measure the applied force to the top corners of the container and the reaction force at the bottom corners of the container. Ten linear variable differential transformers (LVDT) were used to measure the displacement of the container at the point of interest. For all non-destructive and destructive testing, the container was loaded with a load rate of 3 kN/steps and all the readings (from the strain gauge and LVDT) were taken one minute after the loading stopped. The load was increased until either the maximum capacity of the load cell, 80 kN was achieved or the plastic yielding of the container was observed. During the destructive test, 32 strain gauges TML-FLKB-6-11-3LJB-F were also installed on the containers at the point of interest, whereby the maximum stress would possibly occur.

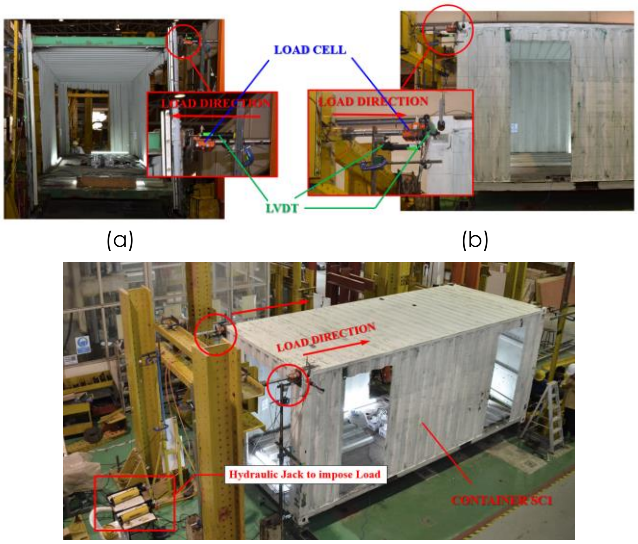


(a) (b)

Figure 1 Detail layout of residential ISO container (a) SC1 and (b) SC2 with dimensions and opening percentage labels with strain gauge location

For container SC1, a non-destructive Test 1 on longitudinal rigidity (Load Case 2) was carried out with the door opened and followed by a non-destructive Test 2a on transverse rigidity (Load Case 1) with the door closed. Then, Destructive Test 2b on transverse rigidity (Load Case 1) with the door opened. For container SC2, non-destructive Test 3a was carried out on transverse rigidity first with the door opened followed by Test 3b with the door closed. After that, non-destructive Test 4a on longitudinal rigidity with the door opened was carried out before destructive Test 4b on longitudinal rigidity with the door closed. The workflow is visualised in Figure 3 with load cases illustrated in Table 1.

All the readings of load cells and LVDT were recorded by using a data logger and inspection of the yielding zone of the container was performed by visual observation. LVDT readings at corners C1 and C2 depicted in Table 1 were validated by using other LVDT data before analysis to obtain an actual deflection.



(c)

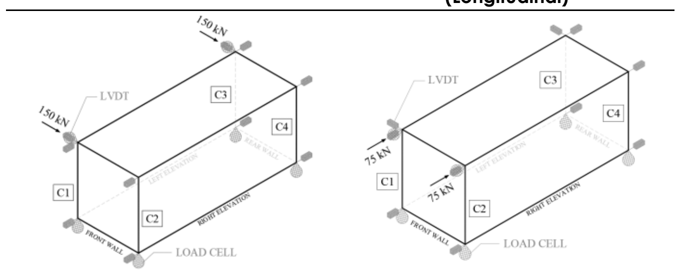
Figure 2 Actual experimental illustration for (a) transverse load direction setup, (b) longitudinal load direction setup, and (c) overall setup for the longitudinal load test

2.2 Finite Element Model of Container Structure

A twenty-foot residential ISO container was selected for this study to conduct numerical modelling and analysis [22]. The container had an external dimension of 6058 mm (length) × 2438 mm (width) × 2591 mm (height). For this model, the steel material used was based on Japanese Industrial Standards, whereby details can be referred to the manufacturer's publication [22]. Finite element software Abaqus/CAE was selected in this study to model and analyse the numerical modelling of the container [23]. Finite element analysis was chosen to observe the detailed structural behaviour of the container model, such as deformation, stress and strain subjected to lateral loading based on different load cases. In this research, model simplification was made by replacing the door assembly with a corrugated wall that exhibited a similar profile as the front wall panel. Besides, details such as reinforcement plate, hinge pin, floor deck and other parts that were not the major contributors to the overall stiffness of the container were excluded from the numerical modelling for simplification purposes. All the assigned steel materials had a density of 7,850 kg/m3, an elastic modulus of 200 GPa and Poisson's ratio of 0.3 which were following MS EN 1993-1-1 [24].

Table 1 Load cases illustration for (a) Transverse Load, and (b) Longitudinal Load [11] with locations of load cells and LVDT

Load case 1: Rigidity (Transverse)	Load case 2: Rigidity (Longitudinal)



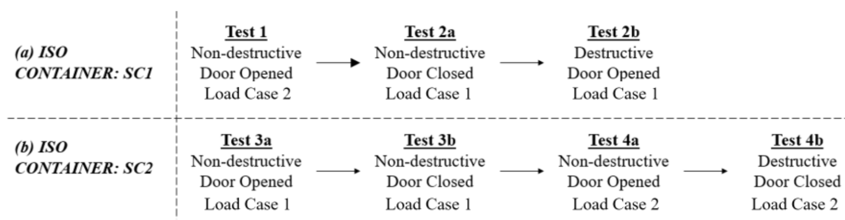


Figure 3 Experimental workflow for containers (a) SC1, and (b) SC2

All parts, except for the base cross member, wall panels and roof were meshed by using a four-node linear tetrahedral solid element (C3D4). For the base cross member, a 3D deformable two-node linear beam element (B31) was selected. The use of C3D4 and B31 elements greatly reduces the consumption of computer resources and yields 3D stress behaviour comparable to that achieved with shell elements. Both wall panels and roof were meshed by using a four-node linear shell element (S4). All connections between corner fittings and structural members (corner posts, side rails, headers, sills) were held together by tie constraint. For wall panels and roof, tie constraint was used to interact shell elements with solid elements. To ensure the accuracy and reliability in the numerical modelling, a mesh convergence test was performed. The results of this convergence test are presented in Figure 4. The maximum displacement recorded during the convergence test was 1.36 mm, which was achieved when using element sizes of 10 mm for C3D4 elements and 25 mm for S4 elements. However, to reduce computational resources, the element sizes were adjusted resulting in a total element count of 1198781 elements. With these adjustments, the deflection values fall under the range of 1.34 mm to 1.36 mm, which is considered satisfactory with less than 0.01 ratio difference. Hence, the mesh properties were decided. Further details of the numerical modelling were described in the study by Ling and Tan [25] in detail.

The bottom corner fittings of the container model were restricted from any translation or rotation by a fixed support boundary condition. Generally, two different load cases were considered separately in the analysis of the container, as shown in Table 1, whereby the load-tested values displayed were specified by the ISO documentation [11]. During simulation, elastic analysis was carried out and the simulation stopped either when maximum load, P_{Max} was achieved or excessive displacement had occurred. The load was exerted at the rate of ($0.01\times P_{Max}$) kN/steps. During simulation, the displacement stress and strain of the deformed container model were recorded.

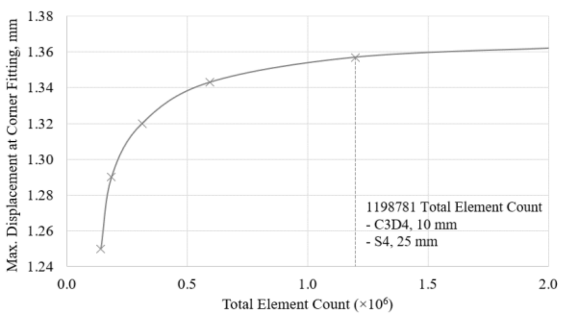


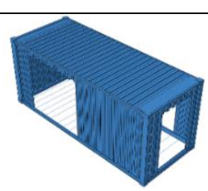
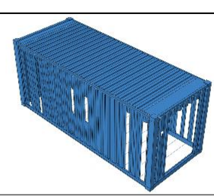
Figure 4 Convergence of maximum displacement with global mesh refinement

Several sets of simulations were carried out based on two different configurations of containers as shown in Table 2. These configurations comprised:

Container SC1: The container wall panel was modified to represent a container specimen for physical test SC1, as illustrated in Figure 1(a). The loading was applied following physical test conditions, as shown in Table 1.

Container SC2: The container model was modified based on the container specimen for physical test SC2, as shown in Figure 1(b). The loading was applied following physical test conditions, as shown in Table 1.

Table 2 Configuration for finite element modelling

Container SC1	Container SC2
	
Load Cases: 1a (Door open), 1b (Door close) 2 (Door open)	Load Cases: 1a (Door open), 1b (Door close) 2a (Door open), 2b (Door close)

3.0 RESULTS AND DISCUSSIONS

3.1 Container SC1 Load Test

3.1.1 Test 1: Load Case 2 with door opened (non-destructive test)

The motivation for transverse load experiment on container CS1 and CS2 are identical to Zha & Zuo [16,17], however the openings ratio and configuration are different. Figure 5 shows the load-deflection curve of Test 1, recorded from the load cells and LVDTs. It was found that the stiffness of corner post C2 was nearly doubled than that of corner post C1. Although the total area of the opening only differed by a small amount (27.5% for the wall between corners C2 and C4 as compared to 29.8% for the wall between corners C1 and C3), the results showed that the reduction of stiffness was not proportional to the opening area. Therefore, a single, large opening would be prone to reduce the wall stiffness more than several smaller openings although the total opening area was the same.

Furthermore, the corner post C1 started to yield at around 10 kN of lateral load, whereas corner C2 could sustain up to 43 kN of lateral load before yielding. With a deflection limit of 8.67 mm in consideration suggested by National Annes to MS EN 1993-1-1[24], a container wall with a single large opening yielded before reaching the deflection limit. For another side with two smaller openings, a deflection of 8.67 mm happened when the lateral load reached 25 kN which was still within the elastic zone. Therefore, for the engineering practice, it is recommended to have two smaller openings for entrance instead of a single large opening on the side wall of the container. This shows that a larger opening greatly reduces the structural stiffness of the container.

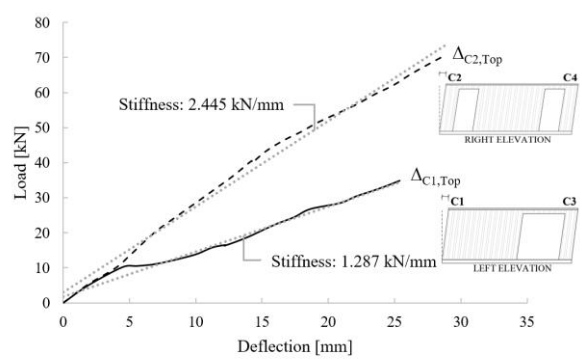


Figure 5 Load-deflection curve for experiment Test 1

3.1.2 Test 2a: Load Case 1 with door closed (non-destructive test)

In Figure 6, the load-deflection graph showed that the stiffness of corner C3 was higher than corner C1. Considering that corner C3 was located at the door end and during this round of testing the door was closed, the transverse stiffness of the front corner post could be considered rigid as compared to the rear corner post. This showed that the corner post of the structure still governed the overall structural stiffness as compared to the walls in the container.

To maintain the lateral deflection of the container within the deflection limit [24] of 8.67 mm, the lateral loading should not be more than 5 kN at the front wall and 4 kN at the rear wall. The transverse strength of the container structure was greatly impaired by the large opening at the wall. Since the container side wall had a larger surface area, it was suspectable towards higher lateral load in the transverse direction, especially when stacked up.

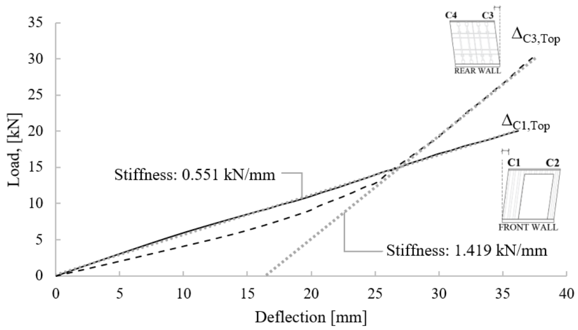


Figure 6 Load-deflection curve for experiment Test 2a

3.1.3 Test 2b: Load Case 1 with door opened (destructive test)

Figure 7 shows the load-deflection graph for Test 2b. As compared to Test 2a, the stiffness of both corner posts C1 and C3 had further decreased due to the opening of the doors. As a comparison of the lower stiffness values amongst Test 2a and Test 2b, the opening of the door had reduced half of the container stiffness.

The ultimate strength of container SC2 obtained under destructive Load Case 1 was 45 kN for the front wall and 22 kN for the rear door. The test was terminated once the instrument reached the maximum reading of deflection. Based on the results, a transverse load of 4 kN and lower was allowed to maintain the deflection under the deflection limit [24] for both sides.

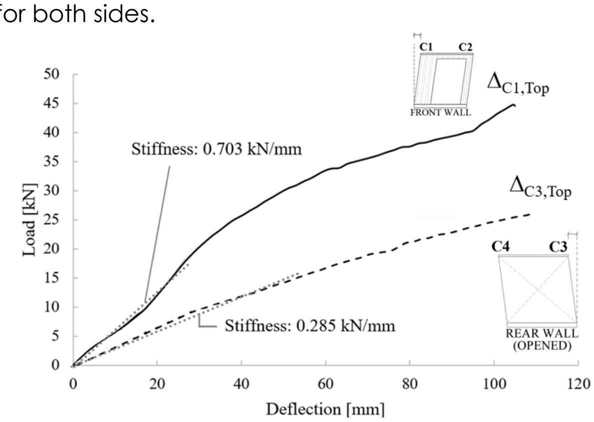


Figure 7 Load-deflection curve for experimental Test 2b

3.2 Container SC2 Load Tests

3.2.1 Test 3a: Load Case 1 with door opened (non-destructive test)

In Figure 8, the overall transverse stiffness of container SC2 with opened door was similar to SC1. However, the stiffness of container SC2 was slightly higher as compared to container SC1 although the front wall of container SC2 had a larger opening. The reduction in transverse stiffness of container SC1 in Test 2b was attributed to its previous loading in Test 2a, which weakened some of its inherent stiffness, thus slightly reducing its lateral resistance. This observation emphasizes the significant effect of pre-test loading conditions on the structural integrity and performance of ISO containers in later tests.

Furthermore, the variation in side wall openings between containers SC2 and SC1 had no impact on their transverse stiffness, indicating that side wall modifications have minimal influence on the transverse stiffness of container structures. Considering the inherent transverse weakness of these structures, it is recommended that modifications be fabricated on the side walls while preserving the front wall to maintain overall structural performance.

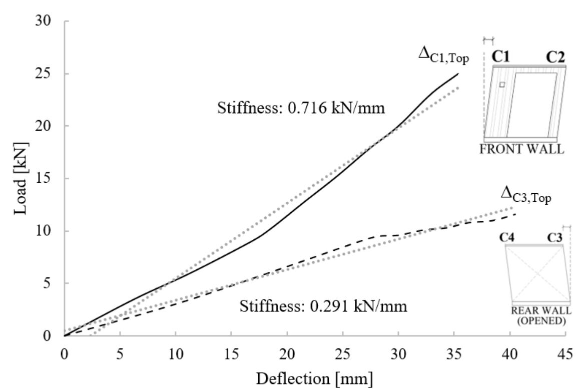


Figure 8 Load-deflection curve for experiment Test 3a

3.2.2 Test 3b: Load Case 1 with door closed (non-destructive test)

By referring to the load-deflection graph for Test 3b shown in Figure 9, the transverse stiffness of container SC2 at corner post C3 was similar to container SC1 in Test 2a. As a comparison, container SC2 transverse stiffness was found higher in the case of Test 3a. However, the rear corner post C1 showed a noticeable increment in transverse stiffness as compared to container SC1 (from 0.551 kN/mm to 0.716 kN/mm). Furthermore, it was believed that due to the loading scheme of SC1 before Test 2a, whereby Test 1 had achieved a higher loading (70 kN).

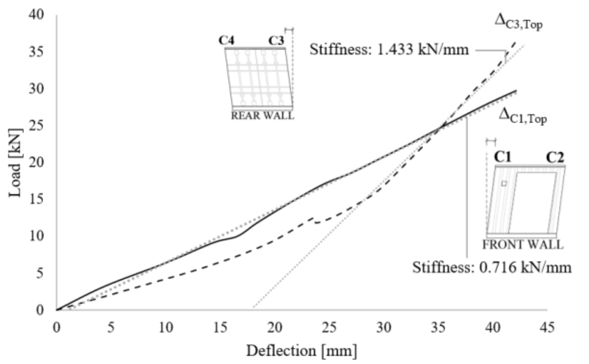


Figure 9 Load-deflection curve for experiment Test 3b

As a comparison for all four tests under Load Case 1, this configuration recorded the highest transverse stiffness value. In short, the container door should be kept closed to have a desirable transverse stiffness for engineering practice. The opening of the front wall should also be kept minimum to increase the overall transverse stiffness.

3.2.3 Test 4a: Load Case 2 with door opened (non-destructive test)

From Figure 10, it is observed that the longitudinal stiffness at corner C1 is higher than at corner C2. The sidewall between corners C1 and C3 features an 11.8% opening area, whereas the sidewall between corners C2 and C4 has a 20.6% opening area. With an 8.8% difference in opening area, the stiffness at corner C2 was reduced by 13.2%. However, this configuration proved more effective than that of SC1, as the lower stiffness of container SC2 (2.449 kN/mm) was still twice that of SC1 (1.287 kN/mm). This indicates a preference for several smaller-sized openings over a few larger ones in container walls. Additionally, this configuration allowed for a lateral load of 20 kN before reaching the deflection limit set by EC3.

However, the transverse stiffness at location C2 for container SC2 (2.449 kN/mm) was found to be similar to that of container SC1 (2.445 kN/mm), even though the opening areas differed by 7%. This indicates that the transverse stiffness of the container is not directly proportional to the total opening area. The arrangement of smaller, closely packed strip openings on the sidewall between corners C2 and C4 in SC2 influenced the stress distribution across the wall panel, reducing its overall longitudinal stiffness. To maintain the structural integrity of container structures, it is recommended that openings be fabricated with optimal size and spacing.

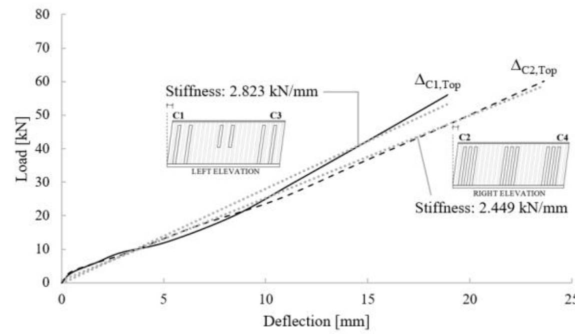


Figure 10 Load-deflection curve for experimental Test 4a

3.2.4 Test 4b: Load Case 2b with door closed (destructive test)

From Figure 11, the stiffness of corners C1 and corner C2 were very much identical to the results from Test 4a. The closing of the door slightly increased the longitudinal stiffness of the container. This test recorded the highest longitudinal stiffness amongst all testings with Load Case 2. The container could sustain up to 18 kN of longitudinal load before reaching the deflection limit [24]. As a comparison to 4 kN of transverse load, it is suggested that the container structure can be designed to bear most of the lateral load from the front wall or door, whereby the local buckling occurs on corrugated panels (see Figure 12).

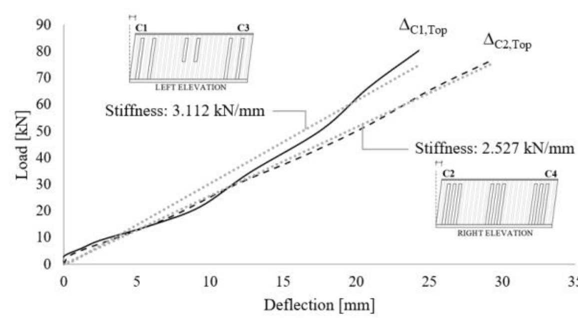


Figure 11 Load-deflection curve for experimental Test 4b

Figure 12 Wall plate buckling for Test 4b

3.3 Strain analysis

3.3.1 Strain of container SC1

From Figure 13, in general, the strain values from the strain gauges installed near the front wall was lower, whereas the strain gauge near the door had a higher reading. Most of the strain values in the front wall were within 0.05, whereas strain values around the door area were within 0.05 to 0.15. The lower strain value around the front wall was believed to be due to the higher stiffness of the corner post around the front wall. Some exceptionally high strain had been recorded at the strain gauge near the corner post C2. This was due to the local yielding of the front header and front sill upon loading as C2 was located opposite of loading side. The opening also led to stress concentration at those locations.

3.3.2 Strain of container SC2

From Figure 14, most of the strain values for container SC2 were within 0.06%. Container SC2 had more evenly distributed strain values across the container, indicating more dispersed stress concentration on this container. It also had a lower strain value overall as compared to container SC1 due to its higher overall stiffness, especially on longitudinal stiffness. The highest strain values were given by the strain gauge attached to the top side beams. This showed that most stress from longitudinal load was distributed from the front wall to the door by the top side beam. The opening of the wall had caused discontinuity and impaired the stressed-skin property of the side walls.

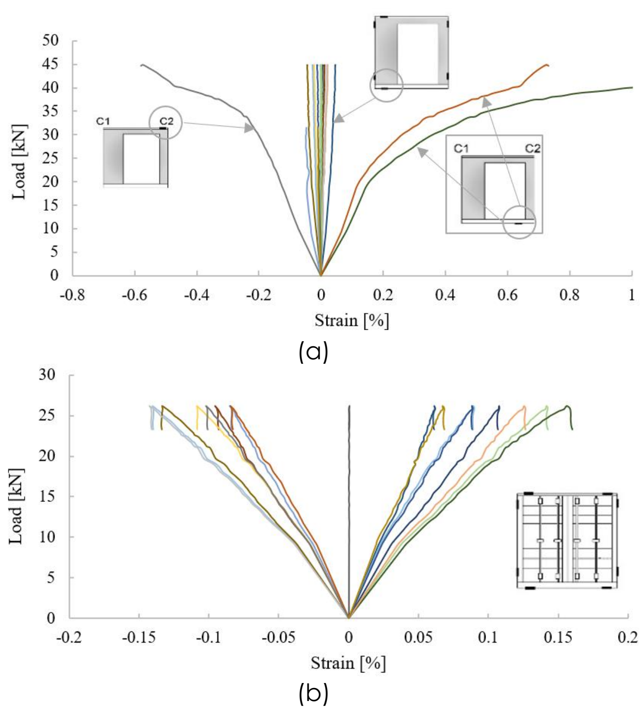


Figure 13 Strain of SC1 for Load Case 1a at (a) front wall, and (b) door

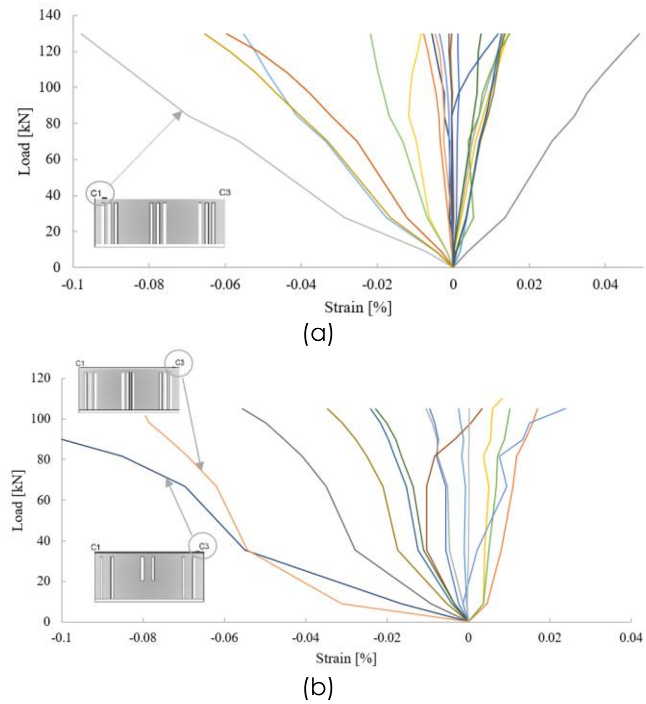


Figure 14 Strain of SC2 for Load Case 2b near (a) front wall, and (b) door.

3.4 Finite element analysis of containers

Table 3 shows the comparison of experimental results between the experimental with the FEM modelling results of container SC1 and container SC2. The difference was represented by the ratio calculated.

Table 3 Table of comparison of FEM and Experimental results

Type	Test/Load Case	Stiffness (kN/mm)		
		C/D: Experimental	E/F: FEM	Ratio (C/E)/(D/F)
SC1	1/2	1.287/2.445[b]	5.97/8.38[b]	0.22/0.29
	2a/1	0.551/1.419[a]	9.02/34.38[a]	0.06/0.04
	2b/1	0.703/0.285[a]	4.17/1.40[a]	0.17/0.20
SC2	3a/1	0.716/0.291[a]	1.68/0.74[a]	0.30/0.11
	3b/1	0.716/1.433[a]	5.34/58.81[a]	0.13/0.02
	4a/2	2.823/2.449[b]	11.54/6.34[b]	0.24/0.39
	4b/2	3.112/2.527[b]	10.12/7.99[b]	0.31/0.32

[a] Result with the format of (Stiffness C1/ Stiffness C3)
[b] Result with format of (Stiffness C1/ Stiffness C2)

3.4.1 Container SC1

Based on results from Table 3 for Container SC1, the stiffness of the finite element model was close to Giriunas [13] but much higher than experimental results for Load Case 1 with the door closed and Load Case 2 with the door opened. The result for Load Case 1 with the door open showed more comparable results than other experimental results. However, the stiffness of container SC1 from the experiment was lower than the stiffness of the container alone under the same loading. This indicated the numerical model was overly constrained leading to a stiffer structure model.

Figure 15 and Figure 16 showed that in neither case the container structure reached the targeted loading. However, the displacement of the container fulfilled the ISO requirement in all cases. To maintain the deflection under 8.67 mm [24], the imposed load shall not be more than 35 kN shown by the critical case of SC1 when the door is opened.

3.4.2 Container SC2

Similar to container SC1, the finite element analysis results were comparable to past research [13] but higher than the experimental results. From Table 3, the governing result was Load Case 1 with the door opened. It can be deduced that the modelling of the container had an issue which was related to the interaction amongst surfaces of the model. In this configuration, the longitudinal stiffness of the container model was higher than its transverse stiffness. The designer is recommended to locate and design the container structure so that the majority of the lateral load is borne from the direction of the front wall or door.

From the load-deflection curve shown in Figure 15 and Figure 16, the container model achieved the ISO load requirement for Load Case 2 but not for Load Case 1. The container model also had less displacement than the ISO requirement under all load cases. To control the deflection under 8.67 mm as per EC3 standard, the transverse lateral load of the container should be limited to 6 kN when the door is opened or 40 kN when the door is closed, and the longitudinal load should be lower than 72 kN whether the door is opened or closed similar to Container SC1.

Furthermore, the overall stiffness of container SC2 was greater than container SC1. Both containers' transverse stiffness was similar, as the major contributor of transverse stiffness, the front wall and door, of the two containers was similar with the only difference being that the front wall in configuration SC2 had an additional 0.4% opening. The longitudinal stiffness of the container was much higher in container SC2 as its total area of opening at side walls was smaller (13.7% and 20.6% of total wall area) as compared to container SC1 (29.8% and 27.5% of total wall area). Since the longitudinal stiffness was sensitive to the area of the side wall removed (removal of 10% additional wall will halve the serviceability load limit), it is recommended to keep as much side wall intact as possible, especially for multi-storey construction, whereby lateral load is significant in design consideration.

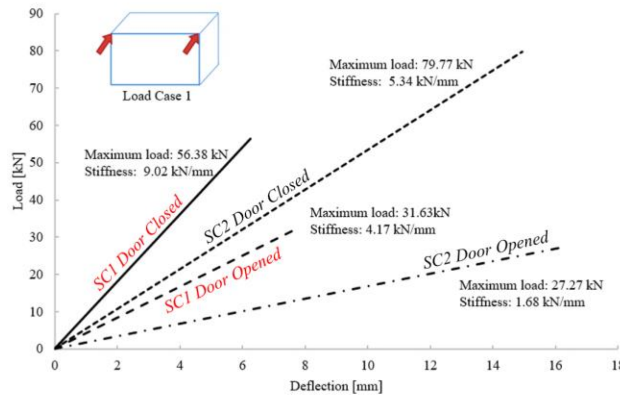


Figure 15 Load-deflection curve for Load Case 1 (FEM Container SC1 and FEM Container SC2)

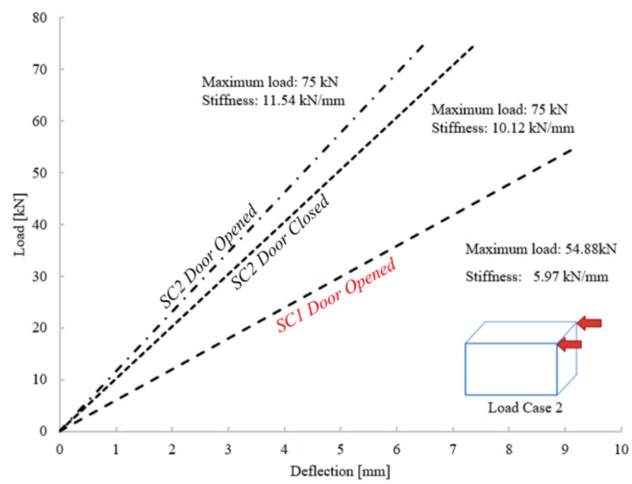
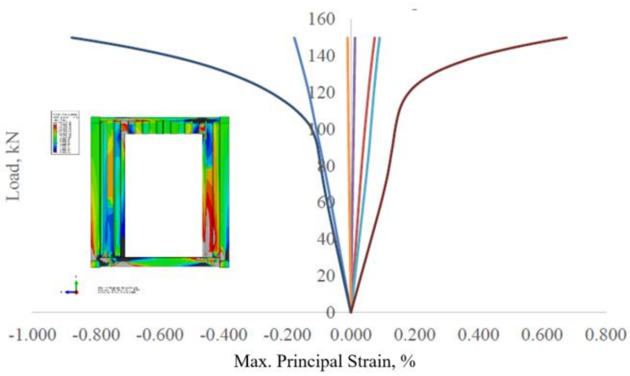


Figure 16 Load-deflection curve for Load Case 2 (FEM Container SC1 and FEM Container SC2)

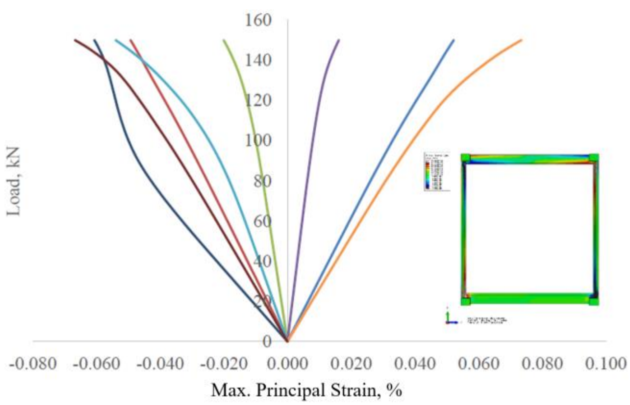
3.5 Finite Element Strain Analysis of Containers

Figure 17 shows several components in the numerical modelling of container SC1 exhibited high strain under loading, specifically at the front sill and door sill. However, the strain value was much lower than the experimental value shown in Figure 13. In the experiment, the door sill did not show excessive strain (comparing Figure 13b with Figure 17b). In general, the load-strain curve for both figures showed a similar trend.

As a comparison of Figure 18 to Figure 14, the strain value was much lower in the numerical analysis. The linear strain profile in the container SC2 numerical model depicted that the model was still under the elastic zone as compared to experiment data, whereby some top side rail had entered the plastic zone.

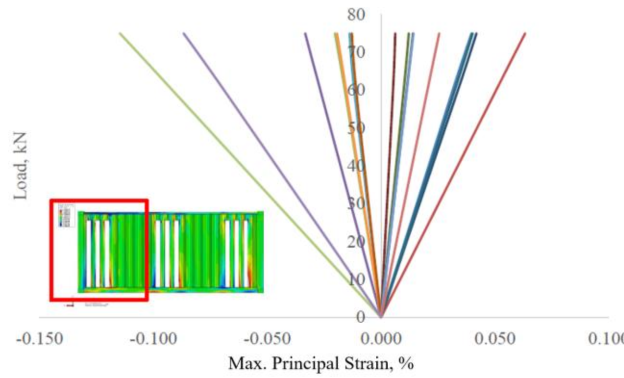


(a)

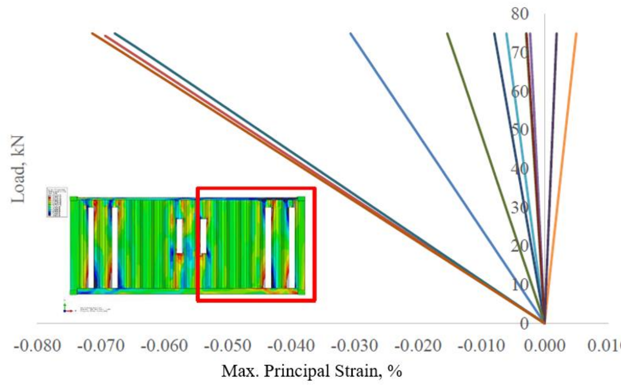


(b)

Figure 17 Strain of container SC1 numerical model during Load Case 1 at (a) front wall, and (b) door



(a)



(b)

Figure 18 Strain of container SC2 numerical model during Load Case 2 at (a) left side wall (b) right side wall

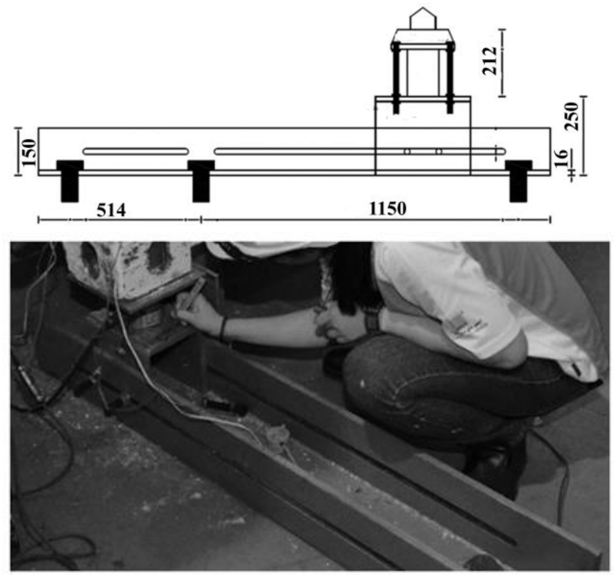
3.6 Comparison of Experimental Results and Finite Element Model of ISO Container Structure

This study adopted the simplification as proposed by previous work [15] for finite element modelling of ISO containers and the results showed that there was a significant difference between simulated result and physical test stiffness. The replacement of the door assembly by using the same profiled panel as the front wall resulted in much higher stiffness in numerical modelling than actual container test results. Aside from the difference in panel geometry, the door assembly of the physical container was made of two separate panels connected by using a locking mechanism (see Figure 19). The separate panels suggested that the physical model had a discontinuity at the panel. This in turn affected load transfer across the door assembly when loaded from the side.

Figure 19 Door assembly of FEM (left) compared to the actual container (right).

The results differences observed in Table 3 occurred from factors that included boundary conditions, connection type and model simplification.

i. Boundary conditions: By comparing the physical model and the finite element model, the boundary condition was found different at the corner fitting on the ground. In the actual test setup, one side of the container was designed to have a roller, as shown in Figure 20, whereas in FEM all four corner fittings were set as a fixed connection that restricted rotations and translation of the bottom member. Therefore, this led to a much stiffer foundation for FEM containers.



(a) (b)

Figure 20 Base system for holding ISO container specimen: (a) schematic drawing; (b) actual view

ii. Connection Types: Tie constraint was used in this study to connect a profiled wall panel to a beam and column. Although this constraint type was mostly adopted and reduced computational power, tie constraint restrained the rotational degree of freedom at the connected node, causing the connected region to be less flexible; and thus larger overall stiffness. To improve the 'similarity' of the physical model and finite element model, Abaqus had a built-in function 'shell-to-solid coupling' as an alternative option. However, the attempt observed that the difference in mesh size between the solid structural member and shell wall panel would lead to an ineffective connection.

iii. Simplification of Model: The simplification in cross-section geometry of the container and the use of the same material properties parameter during modelling was adopted in this study However, several variables unpredictable in actual test setup, such as load eccentricity, material degradation, geometry imperfection which could lead to lower stiffness, were not simulated in FEM.

If the same modelling methodology was adopted to simulate the container behaviour, a reduction factor was proposed to overcome the overestimation of results due to lateral action. On average, a factor of 0.2448 can be used to calibrate FEM lateral stiffness to the actual test result with a regression of 87%, as shown in Figure 21. It should be noted that this factor should be used in conjunction with a proper door assembly modelled for a more representative result.

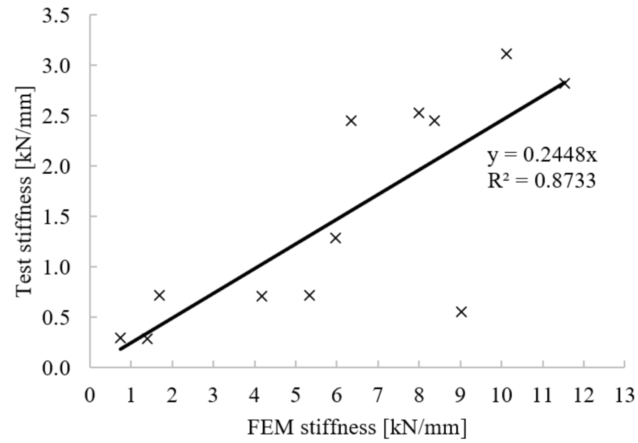


Figure 21 Comparison of test stiffness to FEM stiffness

4.0 CONCLUSION

From this study, a physical test was conducted on two full-scaled residential ISO container structures with various openings fabricated at the container. The container model was tested under two load cases with different configurations of openings at wall panels. This study also developed a finite element model of the container for numerical study. The results from the numerical studies were compared with the full-scale physical tests.

In conclusion, the maximum transverse stiffness of container SC1 when the door was opened and closed was 1.419 kN/mm and 0.703 kN/mm, respectively. This showed that openings in the container structure had a significant impact towards the structural integrity of the container. The maximum longitudinal and transverse stiffness of container SC1 were 2.445 kN/mm and 0.703 kN/mm, respectively when the door was opened, whereas for container SC2 were 2.823 kN/mm and 0.716 kN/mm. Based on these results it was suggested that container SC2 had consistently higher stiffness than container SC1. The opening layout of container SC2 will be more satisfactory for structural consideration with several smaller openings with adequate spacing. Furthermore, the front wall was suggested to be kept intact, as well as closed doors to maintain acceptable transverse stiffness for a container structure. The comparison between the results of the full-scale experimental study and the numerical study showed that both had a significant difference due to the boundary conditions, connections, and simplifications applied in the finite element model. However, to harmonise the results of the numerical study with the experimental study, a reduction factor of 0.2448 was recommended to calibrate the lateral stiffness and achieve an 87% regression with the actual model.

There were some recommendations suggested to extend the work in future research. The numerical model could be refined to achieve more accurate results by using more representative geometry and boundary conditions as actual containers. A parametric study on opening size and location could be done to achieve an optimum configuration of opening for the respective stiffness of the container. Investigation of the effect of reinforcement at the opening on the stiffness of the container can be done. Further research on the effect of loading on container stacks could be conducted to simulate the behaviour of a container used in a multi-story building.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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