






Research Article

Structural evaluation of unitized curtain wall systems by using inter-story drift test

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ABSTRACT

A curtain wall enhances the aesthetic appeal of a building and protects it from harmful environmental conditions. As one of the most significant façade curtain walls, Unitized Curtain Wall Systems (UCWS) are constructed concurrently with the construction of the structural framing system. Because of their lightness, ease of application, functionality, and various design possibilities, UCWSs are frequently used as exterior panels on high-rise buildings. UCWSs must be designed to resist external loads such as wind and seismic load during their lifetime. A structural performance evaluation of the UCWSs is therefore one of the most important criteria for their design. American Architectural Manufacturers Association (AAMA) suggests conducting a full-scale test on a mock-up to determine the structural performance in accordance with AAMA 501.4. In this study, an inter-story drift test was performed according to the AAMA 501.4 standard on a two-story UCWS system, comprised of six panels 1430.8 mm wide and 4215 mm high. The structural behavior of the system was assessed using horizontal and vertical displacement meters that were placed at various points in the system. In addition, a simplified numerical model of the system was prepared and experimental studies were supported by finite element analysis.

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1. Introduction

Curtain walls are popular cladding systems that are used to enhance the aesthetic appeal of building structures and provide a barrier against harmful environmental factors. They are designed to support only their own weight, and they are not intended to make up a structural component of a building. Due to the non-structural nature of curtain walls, lighter and cheaper materials like glass and aluminum tend to be used to build them, helping to reduce construction costs. There are two general categories of curtain wall systems that can be identified today: the stick curtain wall system (SCWS) and the unitized curtain wall system (UCWS). The SCWS is a system of panels that are mainly installed on-site with mullions and transoms through which the expanse of glass, metal panels, and brise-soleil panels are seamlessly linked piece by piece (Fig. 1). In general, each mullion is supported by the

slabs or beams that run along its perimeter. On the other hand, in a UCWS, the curtain wall is constructed of large components that are assembled in a factory, shipped to the site, and installed there. For the mainframe, aluminum profiles which usually stand one story high and are made of light aluminum are used. During the building process, opening vents, glazing, and infill panels are built into the units before they are transported to the construction site. Like in SCWSs, each unit in UCWSs is usually supported by the perimeter slabs and beams. Although vertical mullions elements and horizontal transoms elements surround glass or opaque panels in both systems, at present, the UCWSs with high-quality vertical closures are the most popular for curtain walls on high-rise and large buildings in general (Abdullah and Ronnett 2010). UCWS is generally produced as a single unit consisting of framing system with infill panel in a factory and installed as a single unit on construction site (Fig. 2) while SCWS is gen-

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erally produced as separated framing system and glass infill. Therefore, SCWS systems consist of two stages, first of all, the installation of the frame system in the construction site, and then the assembly of the panels on this

system. The two-stage setup takes longer and is more complicated than UCWS. In addition, since UCWS systems are produced with a standard production system in a factory, the margin of error is less than SCWS systems.



Fig. 1. Stick curtain wall system (SCWS) (Web-1, 2022).



Fig. 2. Unitized curtain wall system (UCWS) (Web-2 2022).

UCWSs of today, although they are considered quite simple, are generally sophisticated products. Therefore, UCWS design guidelines are available from several organizations, such as the European Committee for Standardization (EN 13830), ASTM International Standard (ASTM E1300) and American Architectural Manufacturers Association (AAMA 501.4). These standards have become widely used for guiding in many countries. Furthermore, there have also been numerous scientific studies conducted to evaluate the performance of these systems, as well as the design requirements. As an example, Lee et al. (2021) developed the curtain wall module system and the fastener elements to accommodate displacements and vibrations caused by dynamic seismic waves. Aiello et al. (2018) investigated the seismic loading behavior of

curtain walls in order to contribute to improvements in designing and manufacturing seismic-resilient products. Lee et al. (2017) described how the optimal shapes for a building's curtain wall extrusions can be generated by using a parametrically controlled geometric model and a genetic algorithm. Doebbel (2016) proposed a concept to evaluate the effects of forces and displacements imposed on structural joints as a result of earthquakes occurring on UCWSs. Ilter et al. (2015) compared the structural and infiltration performance of the two identically detailed and manufactured prototypes of a UCWS following the EN 13830 and AAMA 501.4 Standards. Nardini and Al-Hammad et al. (2014) described a systematic approach for the evaluation and selection of curtain wall systems for the construction of medium-high-rise buildings.

In the literature, there have been some studies on UCWSs, but detailed studies on the structural performance evaluation of these systems are scarce. Thus, the purpose of this study was to conduct an inter-story drift test on a full-scale mockup in accordance with the AAMA 501.4 and to evaluate its performance using a finite element analysis based on the results of the inter-story drift test.

A mock-up test is usually preferred to ensure that a curtain wall system can be constructed, integrates correctly, and meets performance requirements. In a properly conducted mock-up test, designers can collaboratively resolve detail and compatibility issues that may arise during construction, verify the functionality of the proposed construction, and apply the results from the tests to the project to avoid expensive, repeated defects. UCWS designs that contain many small details and connections need mock-up tests to ensure they are func-

tioning properly. Therefore, in the first stage of the study, a full-scale mock-up test was performed on a two-stories UCWS model consisting of six panels according to the standard testing protocol outlined in the AAMA 501.4 (Fig. 3). The experimental study was carried out at the Façade Testing Institute in Istanbul using a large test rig. The tests were conducted on a 1:1 scale model of the UCWS model, which had the same characteristics as the real product. As shown in Fig. 3, the test specimens consist of two identically detailed the UCWSs having 1430.8 mm wide by 4215.4 mm high. The systems were constructed of aluminum framing members and insulating glass panels. In this study, the UCWSs were evaluated for their performance when subjected to specified horizontal displacements akin to earthquakes. During the mock-up test, 18 Linear Variable Differential Transformers (LVDTs) were used, and all displacements were instantly recorded (Fig. 4).

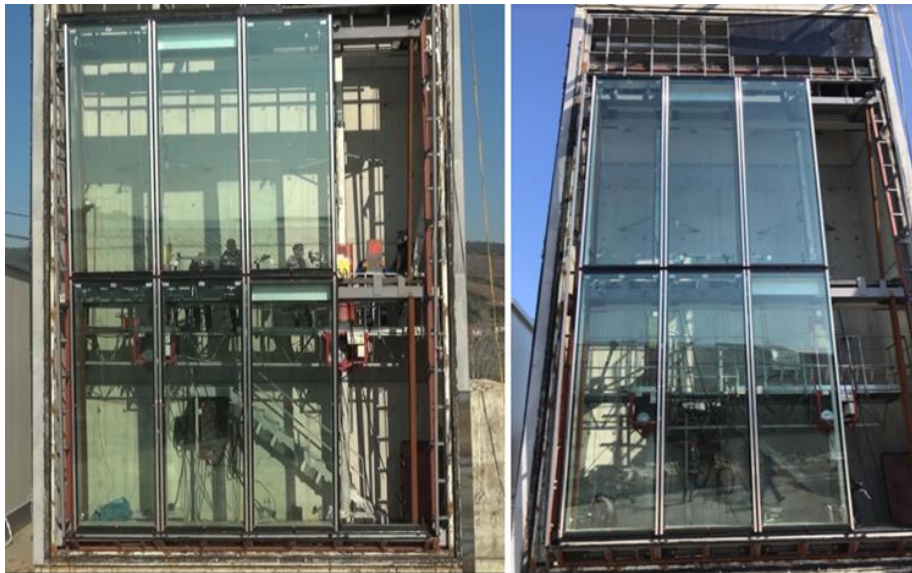


Fig. 3. Full-scale mock-up test.



Fig. 4. Linear variable differential transformers (LVDTs).

AAMA 501.4 defines an inter-story drift test for multi-story mock-ups as a measurement of relative horizontal movements between adjacent stories of a multi-story building. For this reason, a full-scale mock-up was tested for drift across stories in accordance with AAMA 501.4. For inter-story drift tests, the drift amount must equal 0.01 times the story height. Thus, the UCSW system was

pushed in 11 steps from the inter-story section, and a total horizontal translation of 44 mm was applied at the end of the test. Fig. 5 displays the thrust point and LVDT numbers at the measurement points. In Table 1 and Fig. 6, the lateral translations of the LVDTs are presented based on the full-scale mock-up test.

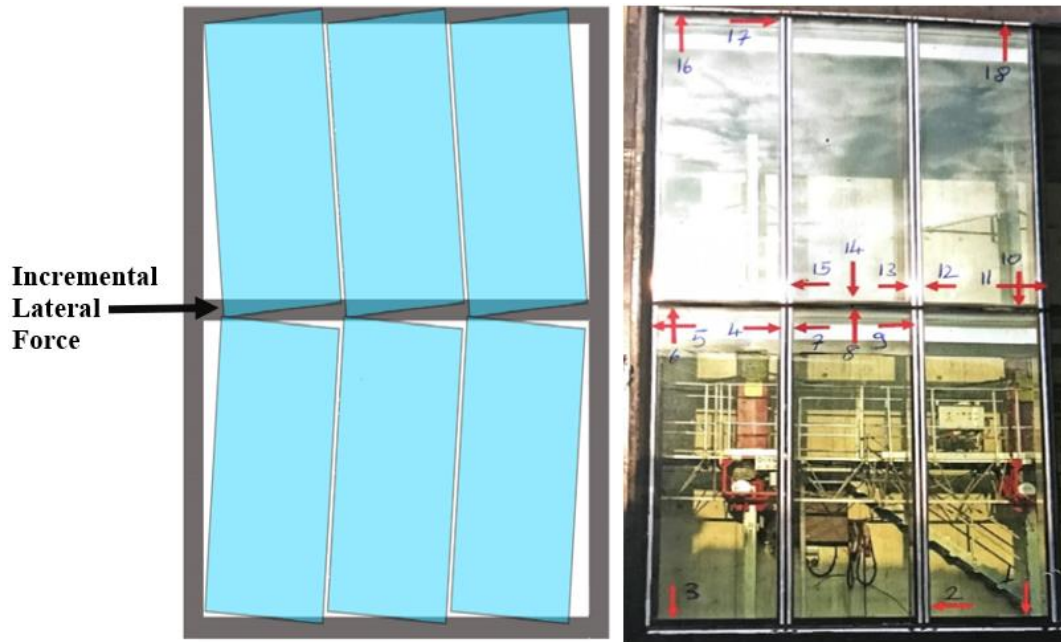


Fig. 5. The inter-story drift test and the LVDT IDs.

Table 1. Full-scale mock-up test results.

LVDT ID	Loading Steps										
	Step-1	Step-2	Step-3	Step-4	Step-5	Step-6	Step-7	Step-8	Step-9	Step-10	Step-11
1	-0,56	-0,91	-1,08	-1,32	-1,38	-1,36	-1,32	-1,37	-1,39	-1,43	-1,55
2	0,35	0,70	0,89	1,20	1,48	1,62	1,73	1,90	2,08	2,28	2,45
3	0,13	0,33	0,50	0,66	0,88	1,04	1,25	1,38	1,54	1,73	1,98
4	-4,04	-7,67	-10,65	-14,57	-18,85	-22,37	-26,01	-30,10	-33,82	-37,59	-41,34
5	4,12	7,84	10,89	14,78	19,19	22,79	26,57	30,61	34,37	38,22	41,88
6	-0,10	-0,31	-0,47	-0,66	-0,84	-1,00	-1,18	-1,31	-1,46	-1,66	-1,90
7	-4,02	-7,72	-10,62	-14,54	-18,92	-22,45	-26,09	-30,26	-33,96	-37,80	-41,58
8	0,00	-0,17	-0,31	-0,52	-0,90	-1,25	-1,79	-2,19	-2,68	-3,18	-3,67
9	3,83	7,54	10,61	14,55	18,85	22,46	26,20	30,28	33,93	37,41	37,41
10	0,28	1,09	1,81	3,16	4,66	5,90	7,28	8,34	9,49	10,65	11,82
11	-3,36	-6,50	-9,36	-13,41	-17,82	-21,50	-25,24	-29,06	-32,58	-36,41	-40,35
12	3,31	6,43	9,09	12,93	17,26	21,01	24,82	28,81	32,47	34,97	34,97
13	-3,67	-6,82	-9,32	-12,55	-16,26	-19,57	-23,14	-27,20	-30,89	-34,75	-38,58
14	0,00	0,03	0,09	0,33	0,89	1,38	2,19	2,84	3,42	4,19	4,93
15	3,64	6,76	9,23	12,48	16,21	19,50	23,04	27,11	30,75	34,61	38,43
16	0,11	0,01	-0,09	-0,18	-0,35	-0,42	-0,57	-0,71	-0,87	-1,06	-1,41
17	-0,65	-0,98	-1,25	-1,56	-1,85	-2,11	-2,27	-2,61	-2,81	-2,98	-3,17
18	-0,29	-0,89	-1,62	-2,71	-4,01	-5,13	-6,30	-7,45	-8,58	-9,73	-10,87

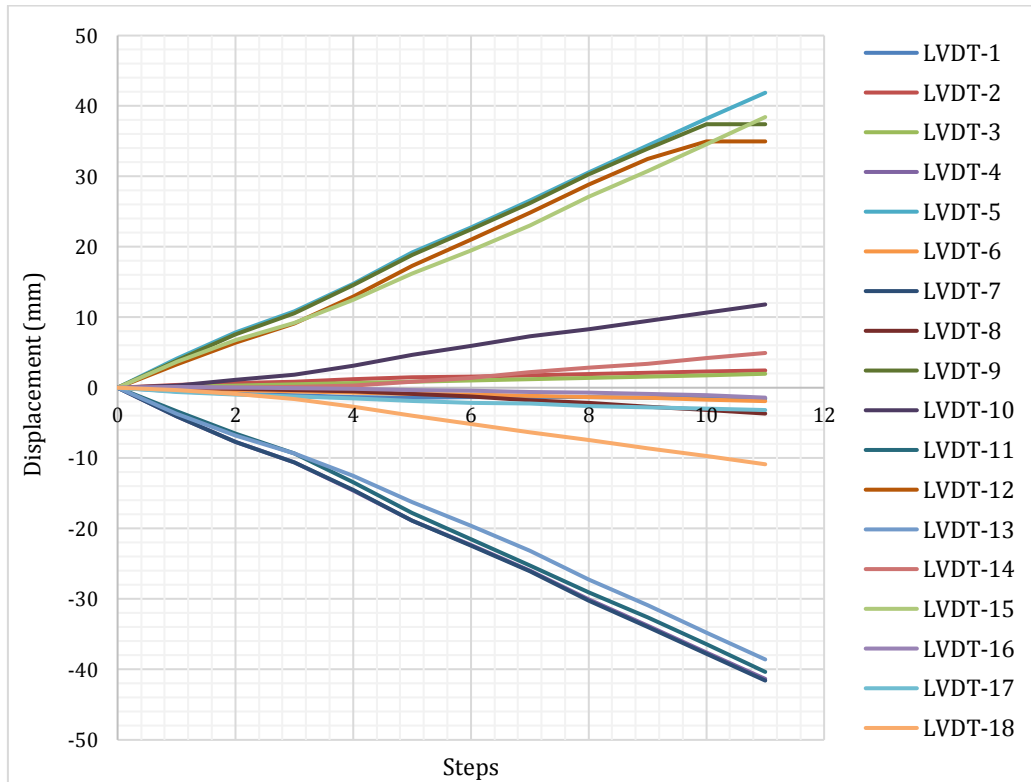


Fig. 6. Displacement records of the LVDTs.

2. Numerical Analysis

2.1. Finite element modeling (FEM)

As part of the second part of the study, the FEM for the inter-story drift test was developed and the finite element analysis was performed according to the loading protocol used to perform the mock-up test. The ANSYS Workbench program was used to build a FEM of the UCWS and some geometric features in the system were simplified while computing the finite element model. In

the first stage of the finite element modeling studies, the entire experimental system was modeled in detail (Fig. 7). A simplification study was then conducted in order to reduce the analysis time of the model by reducing the number of parameters within it (Fig. 8). In the FEM, the simplified model was prepared using 1581533 nodes and 831560 elements (Fig. 9). Based on the operating principle of the system, the bottom and top parts of the panels are defined as fixed to translation and free to rotate as boundary conditions.

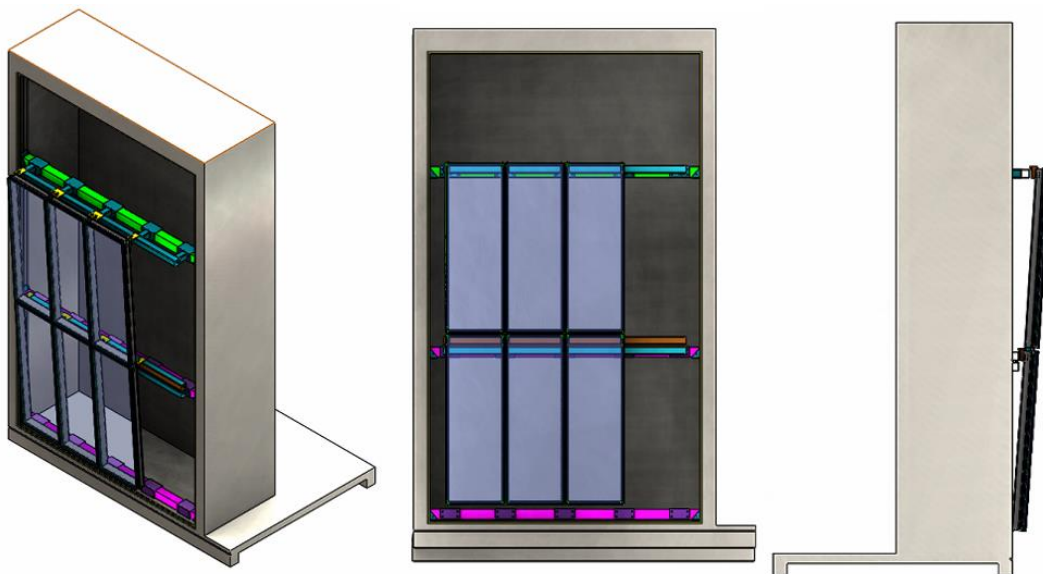


Fig. 7. Detailed 3D model of the experimental setup.

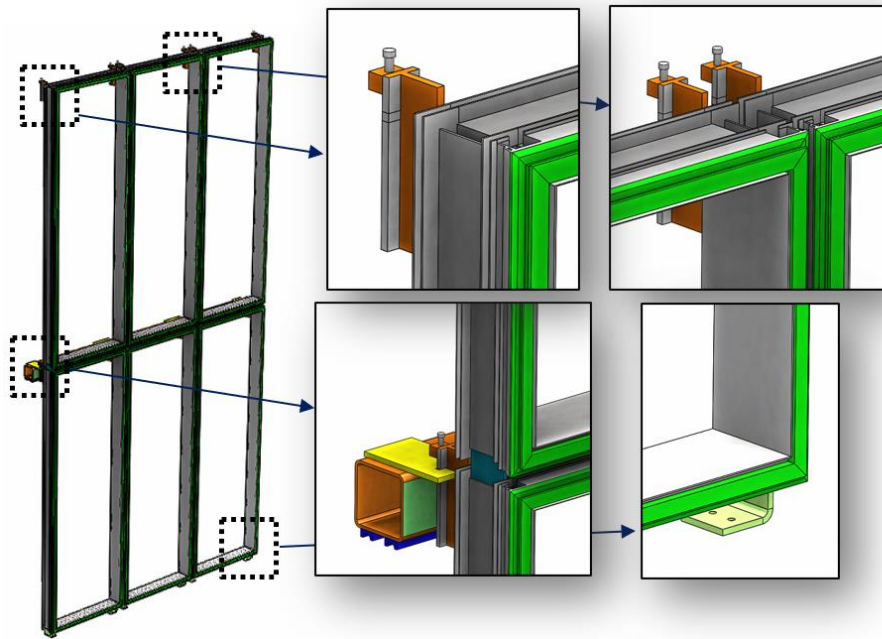


Fig. 8. Simplified 3D model of the experimental setup.

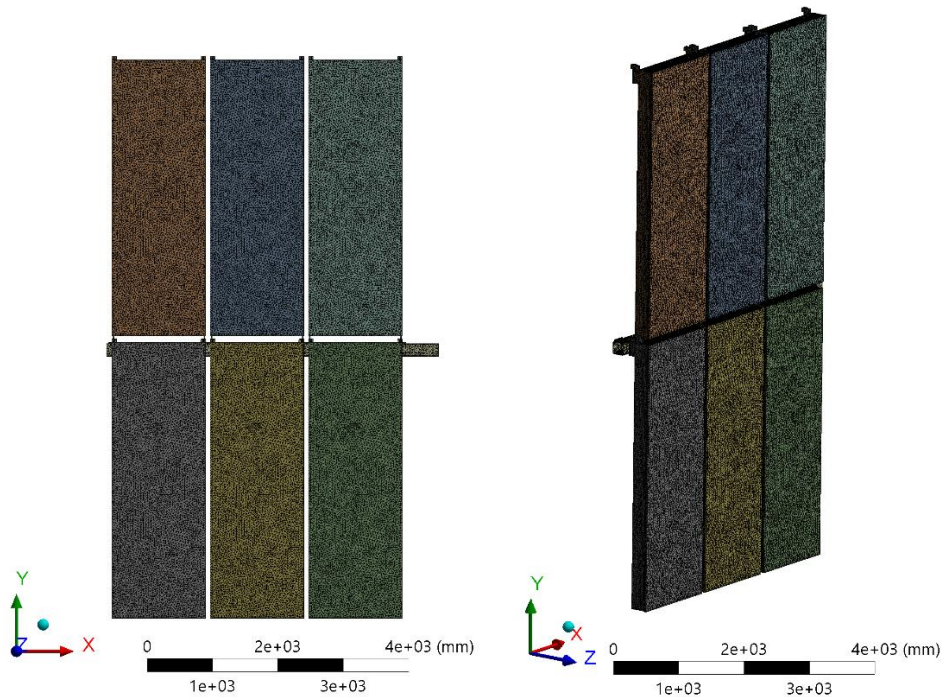


Fig. 9. Simplified finite element model.

2.2. Finite element analysis (FEA)

In this study, the structural components of the UCWS were designed as structural steel, aluminum and glass by considering the experimental system and the properties of the materials obtained from the ANSYS library are summarized in Table 2.

In the FEA, the FEM was applied to 44 mm of lateral displacement over 11 steps based on the experimental results (Fig. 10). At the LVDTs located points, the lateral and vertical displacements were recorded at each step in the FEA. Then, the experimental test and numerical results were compared and checked for compatibility. Re-

lations between the FEA and test results are graphically shown in Fig. 11.

According to the comparisons, it can be concluded that a similar pattern emerged between the experimental and numerical data. Moreover, the FEA results had well symmetry in vertical and lateral displacements. When both the experimental and FEA results were examined, it was seen that the general trend is a linear translation behavior. However, for the LVDT-8 and LVDT-14, the FEA results were a little different from the experimental results. This may be caused by errors in the experimental data or by perfect conditions in the FEM (Fig. 11).

Table 2. Mechanical properties of the structural components.

	Young's Modulus (Pa)	Poisson's Ratio	Density (kg/m3)
Steel	2E+11	0.30	7850
Aluminum	7.1E+10	0.33	2770
Glass	7.2E+10	0.20	2500

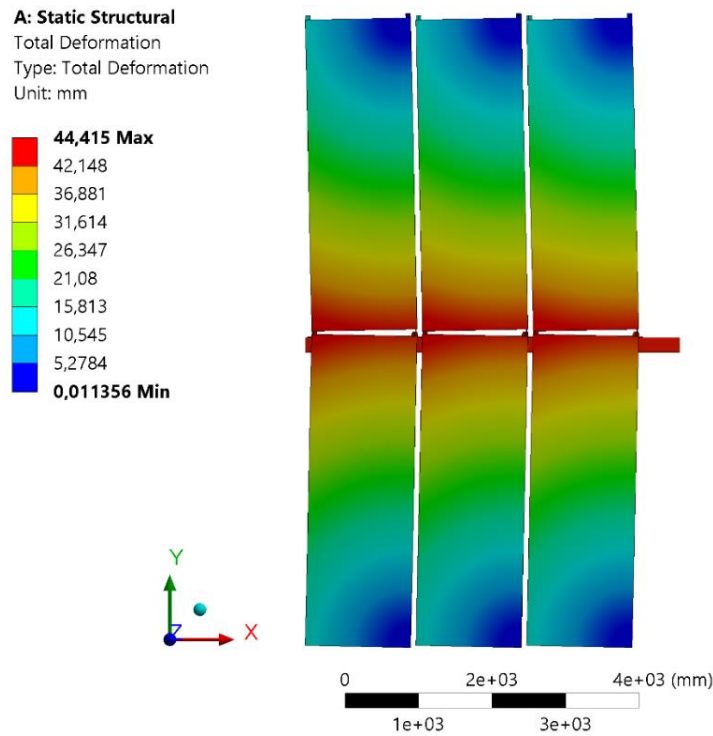


Fig. 10. Total deformation of the system.

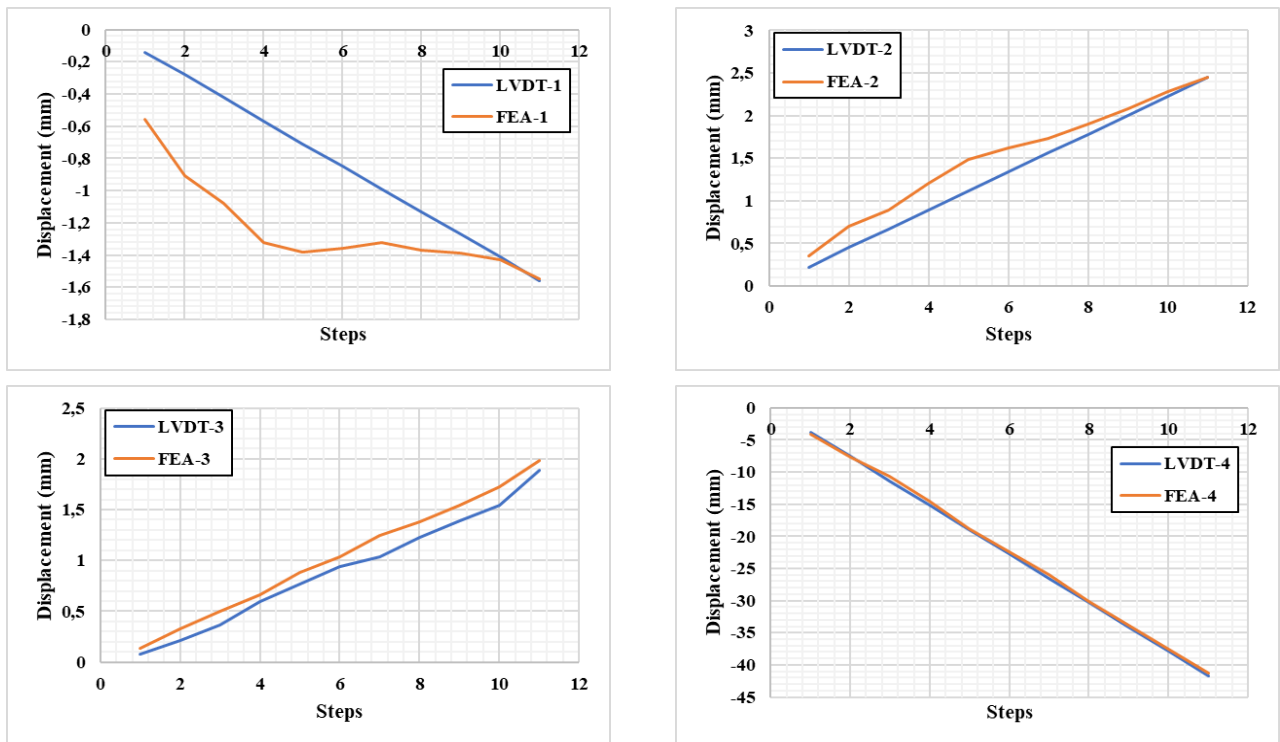


Fig. 11. (continued)

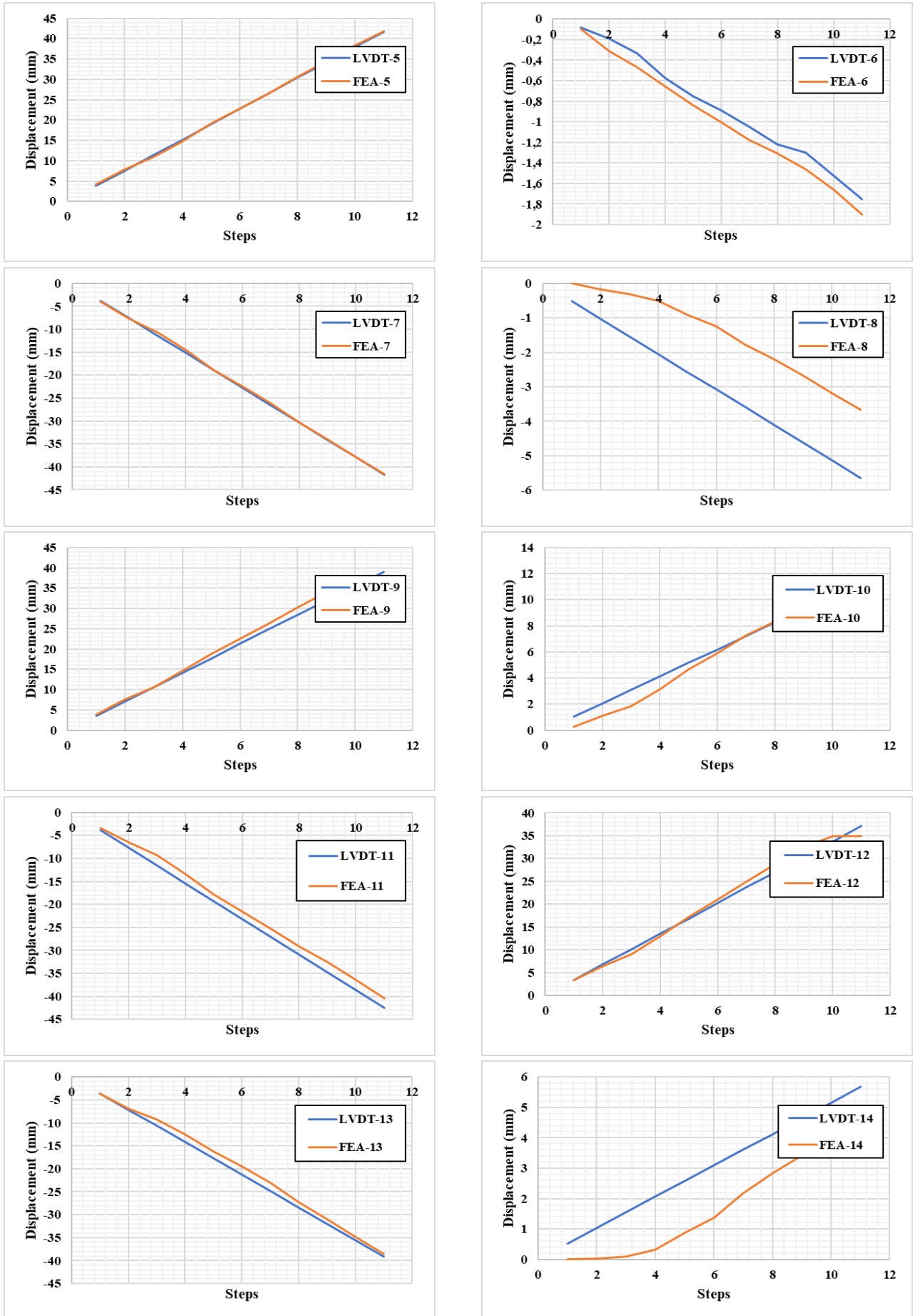


Fig. 11. (continued)

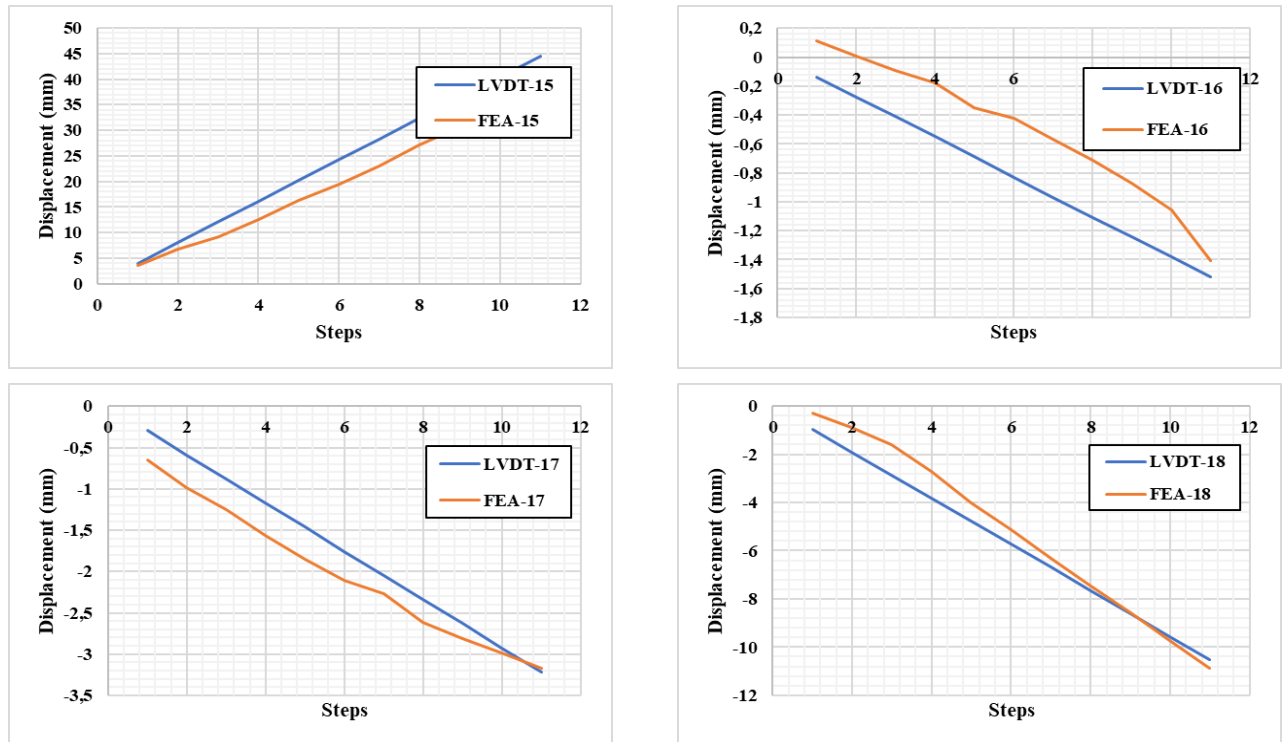


Fig. 11. Comparisons of displacement between experiments and FEA model.

3. Conclusions

The curtain walls of many buildings enhance their aesthetic appeal and protect them from damaging environmental conditions. Unitized curtain wall systems (UCWS) are one of the most significant curtain walls because they can be manufactured concurrently with structural framing. Because of their superior characteristics such as their lightness, ease of installation, and functionality, they are widely used to cover the exteriors of high-rise buildings. The objective of this study is to conduct a full-scale mockup test according to AAMA 501.4 and evaluate its performance based on the results of the inter-story drift test. A large test rig is used as part of the experiment at the Façade Testing Institute in Istanbul. The tests are conducted on a 1:1 scale model of the UCWS, which has the same features as the real product. The UCWS is pushed in a total of 11 steps from the inter-story section and is translated horizontally by 44 mm, which is equal to 0.1 times the story height. During the mock-up test, all displacements are recorded instantly with 18 LVDTs. A simplified numerical model of the system is also prepared to support the experimental studies.

Based on the results obtained from the investigation, it is observed that the wall system was successful according to the AAMA 501.4. Moreover, the data from the LVDTs indicates that the panels exhibit linear behavior, while the system exhibits rigid diaphragm behavior. A similar pattern can be seen in the finite element analysis. It is convenient to see that the records taken from the LVDTs and the records taken from the finite element model are very similar. These results demonstrate that simplification processes are facilitated the numerical modeling of the complex curtain wall systems. It is ex-

pected that the results gotten from this research will become the basis for further research into the same issue. In addition, the dynamic behaviour of the UCWSs should be further investigate through the cyclic loading history.

Publication Note

This research has previously been presented during the 6th International Conference on Earthquake Engineering and Seismology (6ICEES) held in Gebze Technical University, Turkey, on October 13-15, 2021. Extended version of the research has been submitted to Challenge Journal of Structural Mechanics and has been peer-reviewed prior to the publication.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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