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The latest enhancement to Guides of Metal Roof Spatial Structures

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Abstract

IASS Working Group 8 recently published two new guidelines for the design of metal spatial structures: Guide to Buckling Load Evaluation of Metal Reticulated Roof Structures (2014) and Guide to Earthquake Response Evaluation of Metal Roof Spatial Structures (2019). These provided important information for the design of metal roof structures, including buckling and instability, and earthquake response and damage control. Further experimental validation and new findings have been reported over the past decade in IASS annual conferences and other journals. For example, research has been conducted on the stability of free-form gridshell roofs, numerical form finding considering buckling, and seismic design of metal roofs supported by substructures with energy dissipating devices and RC cantilever walls. These studies have been supported by damage observations after recent earthquakes and large-scale shake table tests. This paper summarizes and reviews the latest research on the stability and earthquake response of metal roof spatial structures since the publication of the WG8 guidelines. Trends in in the state-of-the-art and noteworthy studies are discuss and considered of inclusion in the next edition of these Guidelines.

Keywords: metal spatial structures, grid shells, buckling, stability, collapse analysis, seismic response, response control, shake table test

1. Introduction

The overall objective of IASS WG 8 has been to develop and publish structural guidelines for the design and construction of metal spatial structures, together with the reporting and discussion of these techniques and applications. In recent years, WG 8 has focused on four main areas: "Buckling", "Earthquake Response", "Connection Design" and "Realized Projects". For each focus, WG 8 works from the following two aspects:

- Aspect A: Organizing sessions at IASS symposia to promote discussion and exchange of information among IASS members.

- Aspect B: Publication of state-of-the-art reports on metal spatial structures.

A special study group within WG 8 focuses on the buckling and dynamic behavior of lattice roofs, including earthquake response. Under the strong leadership of the members of WG 8, the working group published the "Guide to Buckling Load Evaluation of Metal Reticulated Roof Structures"[1] in 2014 and the "Guide to Earthquake Response Evaluation of Metal Reticulated Roof Structures"[2] in 2019, reflecting the suggestions of the IASS EC reviewers. In the 5-10 years since the publication of these guidelines, new findings have been reported in the annual IASS conferences and journals and are being considered for inclusion in these guidelines. A summary of representative topics is provided below.

2. Progressive collapse phenomena of latticed domes and freeform gridshell roofs

Progressive collapse of single-layer lattice domes poses a serious threat to public safety. Progressive Collapse Resisting Capacity (PCRC) is gradually becoming an essential requirement in the design of spatial structures. At present, the joints used in spatial structures can be divided into welded and fabricated joints. The semi-rigidity of fabricated joints can have a significant influence on the PCRC of single-layer lattice domes. In recent years, studies have been carried out on the PCRCs of single-layer lattice domes with fabricated joints evaluated on the basis of the Critical Progressive Collapse Load (CPCL). Progressive analysis studies and mock-up experiments have also been conducted on the collapse mechanism of single-layer lattice domes with different lattice shapes [3]. Other studies have investigated the stability of free-form lattice shells with joints of varying stiffness and developed form-finding methods to optimize the buckling capacity and stability [4].

These recent results and evaluation methods on the progressive collapse capacity and form-finding approaches to achieve optimal stability performance could be additionally discussed in the "Guide to Buckling Load Evaluation of Metal Reticulated Roof Structures".

3. Seismic response evaluations of freeform gridshell roofs

The seismic response of raised lattice roofs is complicated by the coupled vertical response when subjected to horizontal ground motions. The "Draft Guide to Earthquake Response Evaluation of Metal Reticulated Roof Structures" provides a simple response evaluation method for spherical domes and cylindrical shell roofs that uses amplification factors and equivalent static loads. This method was initially verified for a limited number of idealized shapes, including spherical domes and cylindrical shells, but not for the increasingly popular free-form roof topologies. Recent studies have extended this method to freeform structures using optimization methods and a numerical shape finding process. The effects of parameters such as roof shape, rise-span ratio and supporting substructures on the seismic response have been studied, and distilled into the simple evaluation method [5].

These recent studies and proposals could be incorporated into the "Guide to Earthquake Response Evaluation of Metal Reticulated Roof Structures".

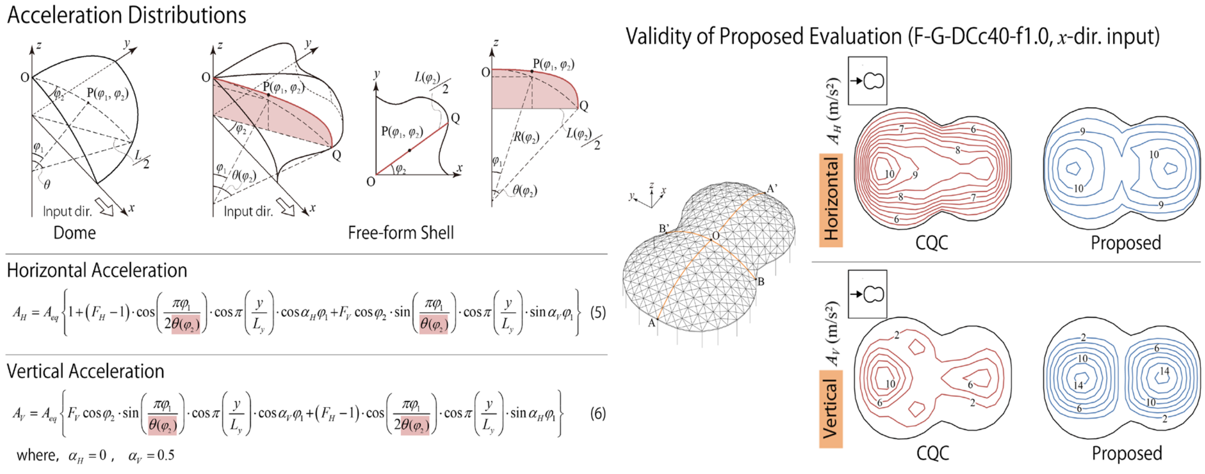

Figure 1: Example of seismic response evaluation proposal for freeform grid shell [5]

4. Damage of gymnasium supported by RC cantilever walls

Damage to steel roofs supported by reinforced concrete (RC) frames has been widely observed in recent earthquakes, as shown in Figure 2. In the 2016 Kumamoto earthquake, buckled and fractured space truss members were observed in two high school gymnasiums, with some members falling and posing a life safety hazard to the students (Figure 3). Subsequent studies clarified that this damage was caused by the out-of-plane response of the heavy cantilevered RC walls and frames, as indicated in the "Guide to Earthquake Response Evaluation of Metal Reticulated Roof Structures", section 3.4.2 (e) “Substructure design of cantilever RC walls”. However, a detailed design method was not yet provided. Followup studies reported in Ref. [6] conducted detailed post-buckling and dynamic post-fracture numerical analysis in conjunction with shake table tests to investigate the failure mechanism (Figure 4). This analysis used a macro-model with a precise representation of the post-buckling hysteresis and fracture mechanism, and successfully reproduced the damage process and failure mechanism of the roofs. In these studies, the load path transfer characteristics caused by the buckling and fracture of the members are discussed and compared with the actual damage. Research has also been conducted into a detailed design method for cantilevered RC walls supporting metal roofs, with the objective to prevent damage to the connection between the bearings and roof. Specifically, a response control methodology that implements friction damper bearings was proposed in the recent studies (Figure 5), [7]. These recent studies and proposals could be incorporated into the " Guide to Earthquake Response Evaluation of Metal Reticulated Roof Structures", section 3.4.2 (e).

Figure 2: Damage of roof bearings supported by cantilevered RC wall [2]

Figure 3: Damage of space frame roof members observed in 2016 Kumamoto Earthquake [6]

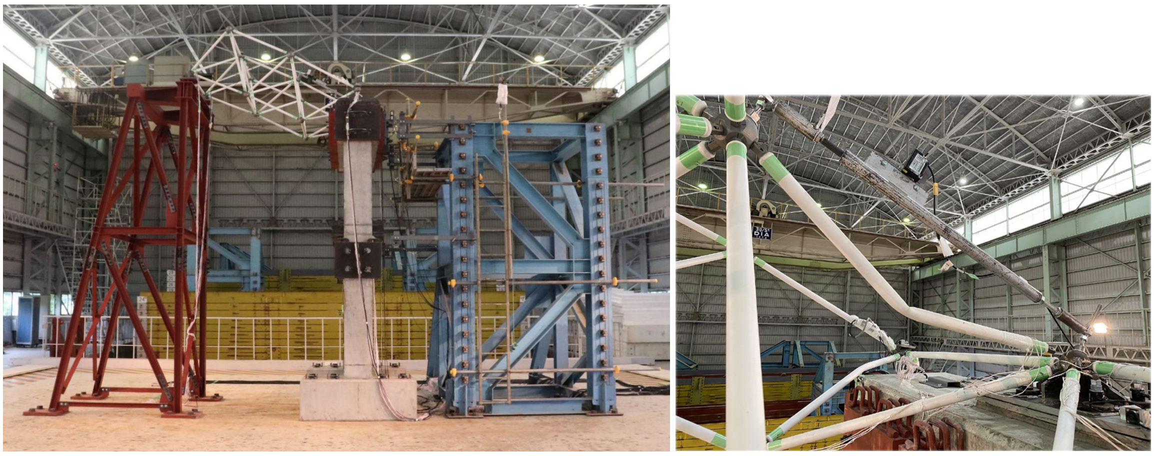

Figure 4: Shaking test for RC walls supporting metal roofs [7]

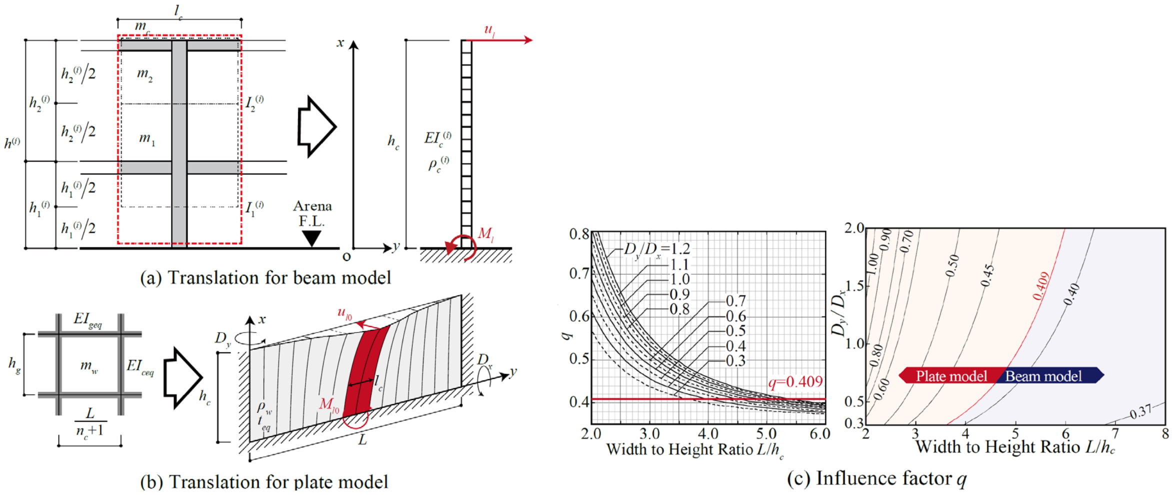

Figure 5: Example of seismic response evaluation proposal for RC walls supporting metal roofs [7]

5. Seismic response of lattice roofs with energy-dissipation devices

As indicated in the "Guide to Earthquake Response Evaluation of Metal Reticulated Roof Structures", chapter 3, raised curved roofs are not only excited in the horizontal direction, but also experience large anti-symmetric vertical acceleration when subjected to horizontal earthquake ground motion. In addition to the coupled response, roofs exhibit closely spaced modes and substructure-roof interaction. Nevertheless, the Guide has proposed elastic horizontal and vertical equivalent static seismic forces to account for these complex dynamic response characteristics. These are determined from the input horizontal acceleration at the roof level of the substructure, an assumed acceleration distribution, nodal roof masses and amplification factors derived from the dynamic characteristics of the roof and substructure. To extend this methodology to elasto-plastic substructures including displacement-dependent damping devices, recent studies investigate the applicability of ductility reduction factors (or R_μ factors) to estimate the inelastic response spectra and an alternative equivalent linearization approach to calculate the peak horizontal acceleration of multi-story substructures with buckling-restrained braces [8]. This is achieved by modelling the curved roof as a rigid mass in a substructure model and obtain the base shear-roof displacement relationship from modal pushover analysis. The peak horizontal acceleration of the substructure is then used to obtain the equivalent static loads of the curved roof using amplification factors. The results compare favorably to non-linear response history analysis. It has been confirmed that the R_μ factors, combined with the roof amplification factors, provide a simple method of estimating the peak roof response with sufficient accuracy for the preliminary design of roofs with multi-story substructures with low post-yield stiffness.

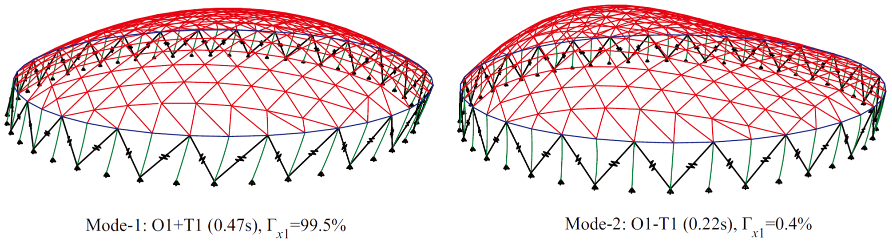

Figure 6: Seismic response modes of grid dome with energy-dissipating substructure [8]

Other approaches to control the response of metal spatial structures with TMDs have been actively studied and recently implemented in practice. One study [9] used three passive added-mass-type vibration control devices, most notably TMDs, and confirm their seismic response control performance both analytically and experimentally. A spatially-distributed multiple-TMD (MTMD) strategy is proposed to effectively control spatial structures, which have more complex vibration characteristics than multi-story frame structures. This is characterized by the control of multiple modes with closely spaced natural frequencies, based on the robust control provided by MTMDs against a spectrum of natural frequencies. This study also proposed using TMDs with initial displacements to improve the transient response. A shaking table test with TMD and comparison of test results and analytical results are presented, as well as a practical application for bridge structures. Although these methods are described in the "Guide to Earthquake Response Evaluation of Metal Reticulated Roof Structures", Section 5.4.3, a more detailed design methodology could be introduced.

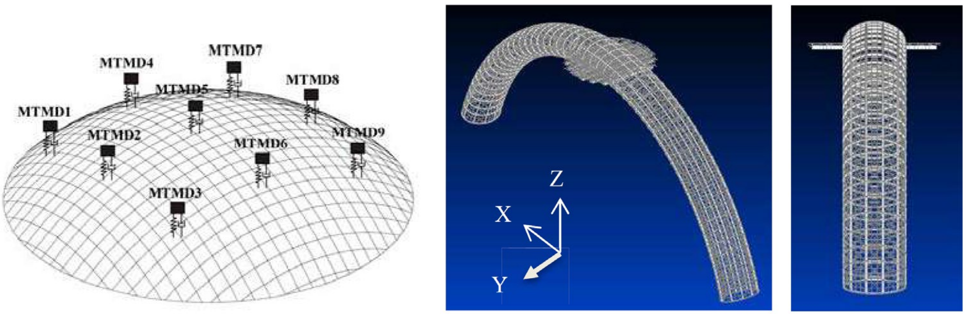

Figure 7: Spatially distributed MTMDs for grid dome and TMD application for bridge structure [9]

A large-scale shake table test was conducted in 2023 at E-Defence, the world's largest shaking table [10]. This test, shown in Figure 8, confirmed the effects of energy dissipation bracing and TMDs, and was continued to collapse mechanism. Future reports on the findings of this experiment are expected, may be reflected in the "Guide to Earthquake Response Evaluation of Metal Reticulated Roof Structures".

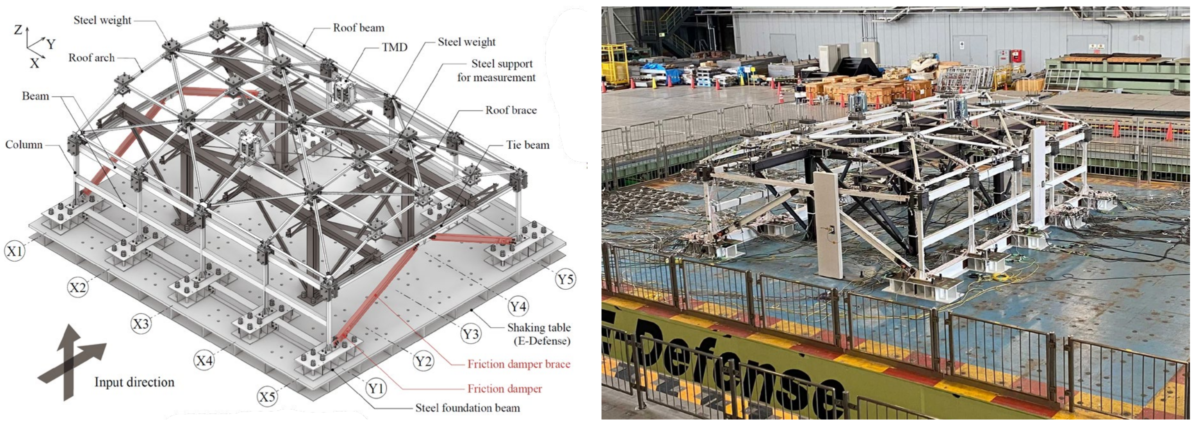

Figure 8: Shaking table test for school gymnasium structure with energy-dissipation braces and TMDs [10]

Conclusive remarks

This paper reviewed and summarized the latest research on stability and seismic response of metal roofs presented at WG8 sessions during annual conferences and the IASS Journal during the years since the Guidelines were published. Key studies and interesting issues that should be considered in the next version of the Guidelines were presented, while further discussion and proposals for updating the Guidelines are expected.

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