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STATE OF THE ART AND EXPERIMENTAL SETUP FOR SEISMIC EVALUATION OF LARGE CONCEALED GRID SUSPENDED CEILINGS

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Abstract

This work focuses on the experimental characterization of concealed grid suspended ceiling systems in semifixed perimeter configurations, with the objective of assessing their seismic performance. Suspended ceilings, as critical non-structural components in buildings, are often susceptible to damage in seismic events, necessitating careful evaluation of their behaviour under dynamic loads. This study provides a thorough review of the state of the art, examining previous research and existing guidelines related to the seismic performance of suspended ceilings. Building on this review, the main contribution of this work is the design and development of a large-scale experimental setup, specifically tailored to test suspended ceilings with an area of up to 50 square meters. The setup will enable future testing under simulated seismic conditions, capturing the dynamic response of the ceiling system. By establishing a robust testing methodology, this study aims to lay the groundwork for future investigations that can enhance the design standards and improve seismic resilience of concealed grid ceiling systems.

Keywords: Non-Structural Components, Concealed Suspended Ceilings, Lightweight Steel, Shake Table Tests, Seismic behaviour.

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1 INTRODUCTION

Non-structural elements, such as partitions, cladding, and suspended ceilings, play a crucial role in ensuring the functionality, aesthetics, and comfort of buildings. Among these, suspended ceiling systems are especially widespread in commercial, healthcare, and educational buildings due to their acoustic properties, ease of installation, and integration with lighting and ventilation systems. However, numerous post-earthquake surveys have shown that these elements are highly susceptible to seismic damage, often resulting in considerable economic losses and, in some cases, posing serious safety risks due to falling debris or blocked evacuation routes.

A 2003 study by Taghavi and Miranda [1] showed that non-structural components and building contents can represent the majority of construction-related costs, surpassing even those of the structural system itself. This underscores the importance of understanding and mitigating the seismic vulnerabilities of such systems. Suspended ceilings, particularly lightweight steel concealed or lay-in grid systems, are among the most frequently damaged non-structural components in earthquakes, especially when they lack proper seismic restraints.

Despite increasing awareness and regulatory attention in recent decades, seismic design of lightweight steel suspended ceilings was largely overlooked in the past, leading to significant failures even under moderate seismic excitations. To address this, experimental investigations have become an essential tool to characterize their behaviour under dynamic loading, particularly given the geometric complexity and non-linear interactions between ceiling grids, hangers, boundary elements, and adjacent structural components. In this context, several experimental studies [2-7] have demonstrated the significance of cyclic loading in predicting the behavior of steel members and components, revealing the potential for degradation in strength and stiffness under repeated seismic actions.

However, a key limitation in the literature lies in the restricted size of the test specimens, mainly due to the physical constraints of most shaking table facilities. Standard test beds rarely exceed a few square meters in size, which does not reflect the real conditions in which suspended ceilings are used. In practice, such systems commonly cover areas exceeding tens of square meters, particularly in open-plan architectural layouts such as offices, airport terminals, hospitals, or shopping malls. The lack of large-scale experimental data limits the understanding of dynamic effects such as wave propagation, boundary interaction, and distributed damage patterns that may develop in actual installations.

To address this gap, this study presents an overview of the state of the art on the seismic performance of large-scale lightweight suspended ceilings tested by means of shaking table test, followed by the design and development of an innovative large-scale experimental setup. The proposed setup allows the mounting and dynamic testing of suspended ceilings up to 50 m^2 in area, overcoming the limitations of standard laboratory infrastructure. Experimental investigations, supplemented by numerical parametric analyses [8-15], can provide valuable insights into the cyclic response of steel components, revealing the impact of various factors on their energy dissipation capacity and overall behavior under cyclic loading.

In the following chapters, a detailed analysis of suspended ceiling systems is presented, beginning with a comprehensive description of their key components and structural configurations. The state of the art of previous experimental activity is then explored. Finally, the proposed setup for assessing the seismic performances of concealed grid ceilings will be discussed.

2 CONCEALED GRID SUSPENDED CEILINGS

2.1 Main features and component

Concealed grid (continuous) suspended ceilings, also known as continuous ceilings, are widely used in commercial, healthcare, and institutional settings. Though non-structural, they enhance fire safety, acoustics, and interior aesthetics. Their seismic performance is critical, as damage during earthquakes can impair building usability and lead to costly repairs.

Unlike lay-in (discontinuous) ceilings, where visible tiles rest on an exposed grid and can be easily removed for access, concealed ceilings use plasterboard panels screwed onto a hidden bi-directional steel grid, creating a seamless, uninterrupted surface. Maintenance access is typically through dedicated hatches, making interventions less flexible than in lay-in systems.

The system includes vertical hangers, main and cross runners, clips or connectors, and plasterboard panels. In seismic regions, lateral bracing, typically diagonal steel struts, is required to counteract inertial forces and prevent detachment or collapse.

A key design aspect is the perimeter boundary condition, which affects how the ceiling responds during seismic events. Configurations can include:

- Fixed: the ceiling edges are fully restrained by perimeter moldings;
- Free-fixed: restraint is applied on two adjacent sides only, allowing some movement;
- Braced: in addition to edge restraints, diagonal braces provide in-plane stiffness.

3 PREVIOUS EXPERIMENTAL SHAKING TABLE LARGE SCALE TEST

Over the past decade, several experimental studies have investigated the seismic behavior of large-scale suspended ceilings through full-scale shake table testing. These studies differ in terms of ceiling configuration, test setup geometry, instrumentation, and loading protocols. The following overview presents a comparative synthesis of the most relevant experimental campaigns in the literature.

In 2016 Ozcelik et al. [16], carried out an experimental characterization on small-scale discontinuous suspended ceilings with fixed boundary conditions along the entire perimeter. The ceilings had an in-plane area of approximately 7 m², and panel unit weights ranged from 16 to 71 N/m². No additional bracing systems were provided.

The test frame was built with steel profiles, with top dimensions of 3.0 × 2.4 m and a height of 1.4 m. These dimensions differed from the shake table size (1.4 × 1.4 m). The bare frame exhibited a natural frequency of 12 Hz in the horizontal direction.

Instrumentation included four uni-axial accelerometers and four string potentiometers to monitor accelerations and displacements.

The input motion followed the ICC-AC156 standard [17], with modifications due to equipment limitations. Recommendations from the IHBC standard [18] were also considered. Motions were applied separately in the two main horizontal directions.

An extensive experimental program investigated discontinuous suspended ceilings under three boundary conditions: fully fixed, fully free, and partially fixed (two adjacent sides fixed, the others free) was presented in Ryu & Reinhorn (2019) [19]. The ceiling areas ranged from 36 to 93 m², and panel unit weights varied from 56 to 197 N/m². Some configurations included bracing systems.

Steel frames were used as test setups, supported by two synchronized shake tables. The small-scale frame was 6.1 × 6.1 m, while the large-scale version was 6.1 × 15.24 m; both were 3.05 m in height. The natural frequencies of the bare small-scale setup were 12 Hz (horizontal) and 22 Hz (vertical). For the large-scale frame, frequencies were 13.5 Hz (long span), 11.4 Hz (short span), and 21.9 Hz (vertical).

Instrumentation comprised 12 tri-axial and 1 uni-axial accelerometer for dynamic monitoring, along with 16 string potentiometers for displacement tracking.

The ICC-AC156 loading protocol was adopted. Input motions included uni-axial (long span), bi-axial (long span + vertical), and tri-axial excitations.

In 2021 Jiang et al. [20], focused on very large-scale discontinuous ceilings, with areas up to 150 m² and a unit weight of 33 N/m². Various boundary conditions were examined: fixed, semi-free, and free. No bracing systems were provided.

The test setup was built from steel profiles, covering a plan area of 12.84 × 11.64 m with a height of 5.4 m. Two shake tables operated simultaneously. The natural frequencies were 8.9 Hz in the long-span direction and 8.4 Hz in the other horizontal direction.

Instrumentation was extensive, including 30 uni-axial accelerometers, 17 displacement transducers, and 140 strain gauges for strain measurement.

Input motions included sweep waves, natural ground motions from the DGJ08-9-2013 standard [21], and artificial waves from the Building Center of Japan, named BCJ-L2, applied either simultaneously or separately in the two main horizontal directions.

Jun et al. (2022) [22] tested both discontinuous and concealed suspended ceilings with free boundary conditions on all sides. Ceiling areas ranged from 16 to 67 m², and hanger loads varied between 43.4 and 76.0 N. No bracing was installed.

The test rigs were built using steel profiles. Depending on the area, either one or two shake tables were used. The small-scale frame measured 4.1 × 4.1 m and was 3.2 m tall. The large-scale setup was 5.10 × 13.1 m with a 3.0 m height. Natural frequencies were 23.0 Hz (long span) and 9.4 Hz (vertical) for the small-scale setup, and 16.8 Hz (long span) for the large-scale setup.

Instrumentation consisted of up to four tri-axial accelerometers and five LVDTs for displacement measurements.

The ICC-AC156 standard [17] was followed. For large-scale ceilings, uni-axial motion was applied along the long span; small-scale tests used uni-axial or tri-axial input.

Finally, Matale et al. [23] focused on concealed ceilings with free boundary conditions. The ceiling area was approximately 7 m², and the unit panel weight was 93.4 N/m². No additional bracing was used.

The test frame measured 3.00 × 2.44 m, was 3.00 m tall, and rested on a 1.50 × 1.50 m shake table. The bare structure exhibited fundamental frequencies of 20.0 Hz (short span), 22.7 Hz (long span), and 15.6 Hz (vertical).

Instrumentation included nine uni-axial accelerometers, two LVDTs, and strain gauges for local deformation measurement.

The shaking input consisted of the N21E component from the 1952 Kern County earthquake (Taft station), applied in two orthogonal horizontal directions.

A comparison of the natural frequencies of the bare test setups highlights a wide variability, primarily influenced by the geometry, mass distribution, and stiffness of the supporting steel frames. In small-scale configurations—such as those employed by Ozcelik et al. (2016) [16] and Matale et al. (2022) [23] the fundamental frequencies in the horizontal direction ranged from approximately 12.0 Hz to over 22.0 Hz. These values reflect the relative stiffness and compactness of the supporting frames. On the other hand, large-scale setups like those used by Ryu & Reinhorn (2019) [19] and Jiang et al. (2021) [20] reported lower horizontal frequencies, ranging from 8.4 Hz to 13.5 Hz, which can be attributed to the increased flexibility of the extended framing systems required to accommodate wider ceiling spans. Where reported, vertical frequencies were generally higher, indicating greater out-of-plane stiffness in all setups.

The use of high-frequency test setups plays a critical role in ensuring the dynamic independence of the support structure from the ceiling system under investigation. A stiff test frame, characterized by natural frequencies significantly higher than those of the suspended ceiling, minimizes undesired dynamic interactions and ensures that the observed response is representative of the ceiling's behavior alone. This prevents coupling effects, artificial resonance phenomena, and distortions in the transmission of the input motion, thereby improving the accuracy, reliability, and repeatability of the results. High-frequency setups also enable closer compliance with standardized loading protocols, such as ICC-AC156, by delivering cleaner and more consistent input motions.

Despite the inherent limitation posed by the restricted size of conventional shaking tables, all the reviewed experimental studies successfully devised tailored test setups that allowed for the investigation of large-area suspended ceilings. This was achieved by designing independent steel support frames that extended beyond the dimensions of the shake tables, effectively decoupling the ceiling specimen's span from the actuation platform's footprint. In many cases, multiple synchronized shake tables were employed to drive larger setups, while the superstructures were engineered to reproduce realistic boundary conditions and dynamic properties. These methodological solutions enabled the reproduction of complex ceiling configurations (both in terms of geometry and boundary restraints) while ensuring the applicability of the results to full-scale systems. In the discussed researches, the authors achieved a delicate balance between experimental control and representativeness, offering valuable insights into the seismic performance of ceilings at realistic scales.

4 PROPOSED TEST SET UP

4.1 Shaking table main features

The experimental campaign proposed in this study will be carried out in the Laboratory of the Department of Structures for Engineering and Architecture at the University of Naples "Federico II." The shaking table available in this facility features plan dimensions of 3.0 x 3.0 meters and is capable of supporting a maximum payload of 200 kN. The system operates within a frequency range of 0–50 Hz, with a peak velocity of 1 m/s, a peak acceleration of 1 g, and a displacement capacity of ±250 mm. The table provides two degrees of freedom in the horizontal plane and no vertical actuation. Although two identical shake tables are available at the laboratory, only one will be employed in the testing campaign. As in previous studies, a steel frame will be designed to extend beyond the shaking table's dimensions and recreate realistic boundary conditions for large-area ceilings, ensuring the experimental validity and scalability of the results.

4.2 Set-up main geometrical features

The experimental set-up has been designed to accommodate the testing of suspended ceilings over a surface area of up to 50 m². The base of the set-up consists of a 3 m × 3 m vibrating table, onto which a steel-framed reticular structure has been mounted. This structure serves both as a support system and as a boundary condition for the ceiling specimens under investigation.

The upper portion of the structural frame is composed of steel reticular beams, onto which secondary structural members are affixed for the connection of the ceiling hangers. The reticular beams employ L-shaped profiles for the diagonals and paired L-shaped profiles for both the upper and lower chords. The total height of each upper reticular beam is 0.8 m.

At either end, the reticular beams rest on a lateral resisting system constructed from paired UPN 300 profiles, providing a total column height of 1.7 m. The space between the lower chord of the reticular beam and the top of the lateral resisting system—referred to as the *gap*—constitutes the available region for positioning the suspended ceiling grid. This gap measures 0.6 m in height.

The configuration includes two lateral resisting systems in each principal direction to ensure adequate in-plane stability. Depending on the positioning of the hangers, the set-up allows for the testing of suspended ceilings with overall heights ranging from 0.9 m to 1.3 m when the ceiling is suspended from the upper chord, or from 0.1 m to 0.5 m when suspended from the lower chord of the reticular beam.

The choice of structural profiles was driven primarily by stiffness requirements, while the specific section types (L-shaped and paired UPN profiles) were selected for their ease of interconnection and assembly.

In terms of mass, the estimated self-weight of the structural set-up, including the secondary elements used to suspend the ceiling, is approximately 9.5 tonnes. Assuming a typical heavy suspended ceiling system with a unit weight of approximately 35–40 kg/m², the total weight of a 50 m² ceiling would be in the range of 1.75 to 2.00 tonnes. Therefore, the combined mass of the set-up and a heavy ceiling specimen reaches approximately 11.5 tonnes.

Given that the payload capacity of the shaking table is 20 tonnes, the set-up enables the testing of a wide variety of suspended ceiling configurations, ranging from lighter systems (e.g., mineral fiber or lightweight metal tiles) to heavier assemblies (e.g., gypsum board or concrete-based panels), within the allowable dynamic load limits.

A schematic 3D view of the overall set-up is shown in Figure 1, while Figure 2 illustrates a detailed cross-sectional view of one of the lateral resisting systems, including relevant dimensions.

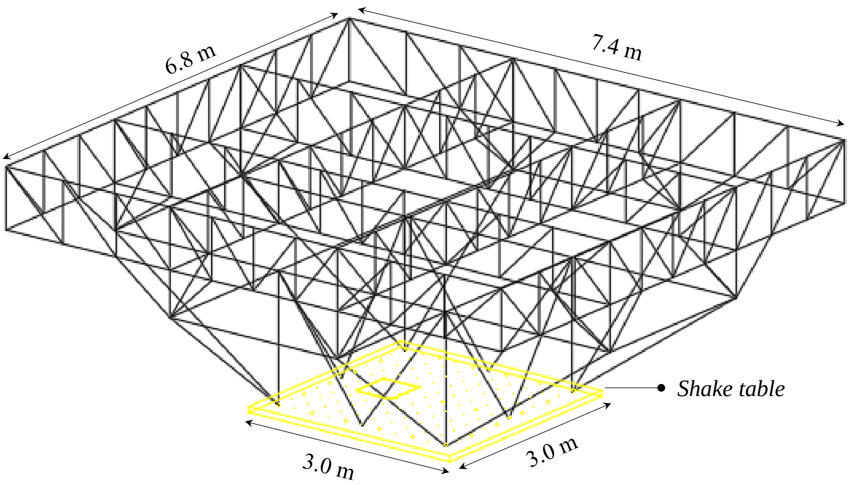

Figure 1. 3D view of the proposed test set-up

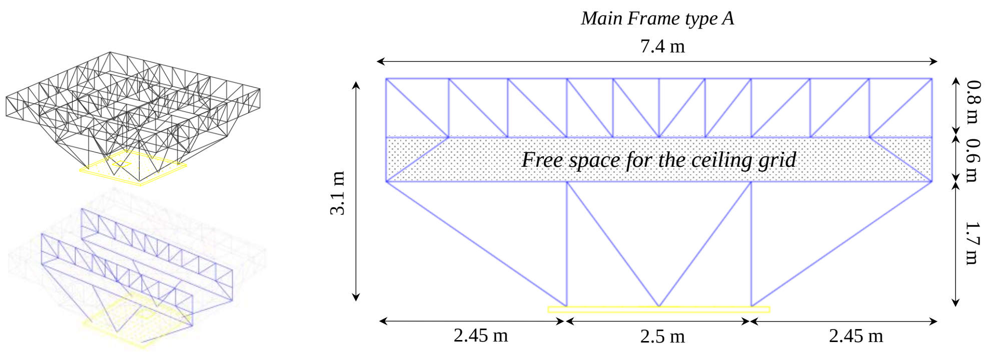

Figure 2. Schematic view of the upper truss beam and lateral force resisting system

4.3 Modal properties

A preliminary modal analysis of the test set-up was performed numerically under bare-frame conditions, i.e., in the absence of any suspended ceiling components. The results indicate that the first two modes are predominantly translational in the horizontal plane, while the third mode corresponds to a rotational motion around the vertical axis. The associated periods and frequencies are summarized as follows:

- Mode 1 (translational): $T_1 = 0.0317$ s, $f_1 = 31.6$ Hz
- Mode 2 (translational): $T_2 = 0.0314$ s, $f_2 = 31.9$ Hz
- Mode 3 (rotational): $T_3 = 0.0311$ s, $f_3 = 32.1$ Hz

These results demonstrate a high global stiffness of the supporting frame and reflect the intended design objective of achieving a dynamically rigid structure relative to the ceiling components under investigation.

Compared to previous experimental test setups reported in the literature, which typically exhibit fundamental frequencies in the 8.4–23.0 Hz range (corresponding to periods between 0.043 s and 0.119 s), the present set-up is significantly stiffer. This higher stiffness ensures that the dynamic response of the frame remains decoupled from that of the suspended ceiling, minimizing undesired interactions and enabling a more accurate representation of the ceiling's seismic behavior. The elevated natural frequencies confirm that the supporting structure behaves as a nearly rigid boundary condition, in line with the design objectives and international testing recommendations.

5 CONCLUSION

Non-structural elements, such as suspended ceilings, are essential not only for the functionality and aesthetics of modern buildings but also for ensuring occupant safety and post-earthquake usability. Despite their non-structural nature, numerous seismic events have demonstrated how damage to these components can lead to significant economic losses, obstruction of evacuation routes, and, in some cases, life-threatening situations.

Over the past two decades, various experimental studies have investigated the seismic response of suspended ceilings using shake table testing. However, a major limitation shared by most of these works is the reduced size of the ceiling specimens, often constrained to areas of less than 10 m², due to facilities limitations.

To address these limitations, the present study introduces an innovative large-scale experimental setup specifically designed to test suspended ceilings with plan areas up to 50 m². The configuration is based on a high-stiffness steel frame mounted on a single 3.0 × 3.0 m shake table, equipped with two horizontal degrees of freedom. Modal analysis of the bare setup demonstrates that the first three natural frequencies exceed 31 Hz, confirming that the frame behaves as a dynamically rigid support relative to the suspended ceiling system.

Compared to the experimental setups reported in the literature, the proposed configuration exhibits a markedly higher dynamic stiffness, ensuring minimal interaction between the support structure and the tested ceiling. This is a critical feature, as it allows the recorded response to more accurately reflect the intrinsic behavior of the ceiling components under seismic loading. By eliminating undesired resonance and dynamic coupling effects, the proposed test rig enhances the reliability and reproducibility of the experimental results.

The ability to test large-area ceilings with realistic boundary conditions and under multi-directional seismic input makes this setup a powerful tool for assessing the seismic vulnerability of both concealed and lay-in suspended ceiling systems. The outcomes of future experimental campaigns based on this setup are expected to significantly contribute to the development of improved design guidelines and qualification procedures, ultimately promoting safer and more resilient building interiors in seismic regions.

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