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INVESTIGATING THE PROTECTIVE CAPABILITIES OF EARTHQUAKE DESKS THROUGH COMPRESSION AND SHOCK TABLE TESTS

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Abstract

This paper describes a series of physical tests conducted on Earthquake (EQ) Desks manufactured in Nepal to determine their capacity and improve the understanding of their performance under falling debris during a seismic event. The testing program included five vertical compression (static) tests and a dynamic shock table test. The desks tested included both secondary (high) school and primary (elementary) school sizes, with some featuring new plywood panel ”side protection” to evaluate its effectiveness. The compression tests were aimed to quantify the vertical load and displacement capacities of the desks, as well as their energy absorption capabilities. Results indicated that the desk capacity is highly dependent on the loading application, with a minimum elastic load capacity of 45.7 kN, a minimum peak load capacity of 98.2 kN, a minimum peak displacement capacity of 92 mm, a minimum elastic energy capacity of 0.28 kJ, and a minimum total energy capacity of 7.05 kJ. During the dynamic shock table test, six EQ Desks were subjected to the complete collapse of a full- scale mock-up school classroom. The single-story mock-up building was constructed with two unreinforced stone masonry walls with mud mortar and slate stone roof. The other two sides of the structure were left open. Observations revealed that EQ Desks experienced impacts from stone walls and roofs separately. A significant finding was that although the lateral debris wave pushed some desks, none toppled. EQ Desks with side protection demonstrated a reduction in debris entering the ”safety-zone” below the desk. Importantly, all EQ Desks sustained only minor cosmetic damage to the plywood desktop and edging, successfully maintaining their full ”safety-zone” throughout the tests, and no simulated occupants (water containers) were punctured, indicating non-lethal injury to children. The vertical demands observed during the shock table test were found to be below the minimum elastic load and energy capacities of the desks. These findings confirm the robust performance of Nepal-built EQ Desks, supporting their appropriateness as a protective solution in single-story stone masonry buildings and potentially two-story structures.

Keywords: Earthquake desks; Seismic protection; Physical testing; Debris loading; Classroom safety

1. Introduction

Earthquake vulnerability remains a critical concern for school infrastructure across Nepal, where unreinforced stone masonry construction is prevalent, some with heavy mud and slate roofs. The Earthquake Desk is an innovative

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protective device designed to maintain a survivable void beneath falling debris during building collapse. While prior drop tests conducted in Italy and Bhutan demonstrated the vertical impact resistance of EQ Desks, critical knowledge gaps persisted regarding their performance under dynamic collapse conditions reflective of real earthquakes.

To address these uncertainties, a comprehensive testing program was conducted that included both compression (static) tests and dynamic shock table tests using a full-scale classroom mock-up. This study aimed to assess whether EQ Desks manufactured in Nepal can effectively protect occupants during actual structural failures and to collect quantitative data to inform design improvements and deployment strategies.

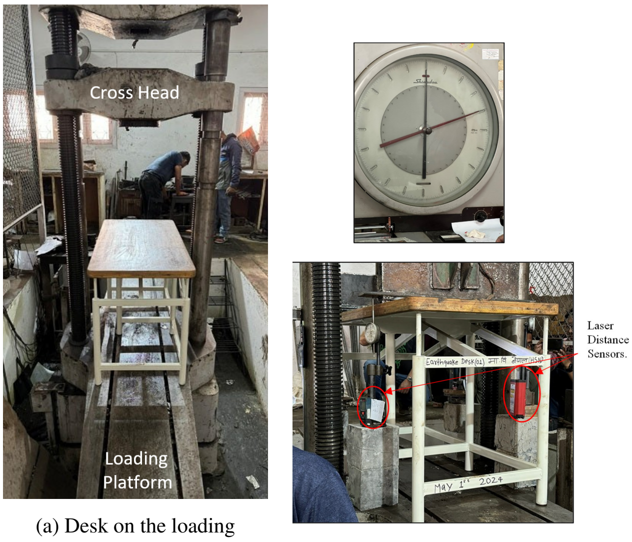
2. Objectives

The EQ Desk testing program was designed to achieve several objectives. The compression (static) tests aimed to determine the vertical load capacity, stiffness, and energy absorption of full-scale, locally manufactured desks to establish baseline strength and deformation characteristics. The dynamic shock table test simulated the complete collapse of a full-scale stone masonry classroom to evaluate the desks' performance under realistic impact, debris motion, and lateral displacement. Together, these tests provide a comprehensive understanding of the EQ Desks' ability to preserve a survivable safety-zone under both controlled static loading and complex dynamic collapse conditions. Additionally, the experiment sought to determine whether EQ Desks preserve their designated safety-zones when subjected to simulated earthquake loading. Finally, observations of damage modes and desk displacements were intended to guide future refinements of both analytical demand estimation methods and the physical design of the desks.

3. Compression (Static) Tests

3.1. Experimental Test Set-ups

Compression tests were conducted at the Central Material Testing Laboratory, Pulchowk Campus, Institute of Engineering of Tribhuvan University, Nepal. A universal testing machine (UTM) with a steel load beam was used to apply the loading to the EQ Desks. This UTM machine was selected because it allows for very good load control. The testing machine has a dial load gauge to measure the applied load (see Figure 1a). Laser distance sensors measured the displacements of the desk due to the applied loads (see Figure 1b). Four laser distance sensors were used for the first two tests and placed at the corners of the load beam to measure the relative movement between the load platform and the load beam corners.



(a) Desk on the loading platform

(b) UTM load gauge and laser distance

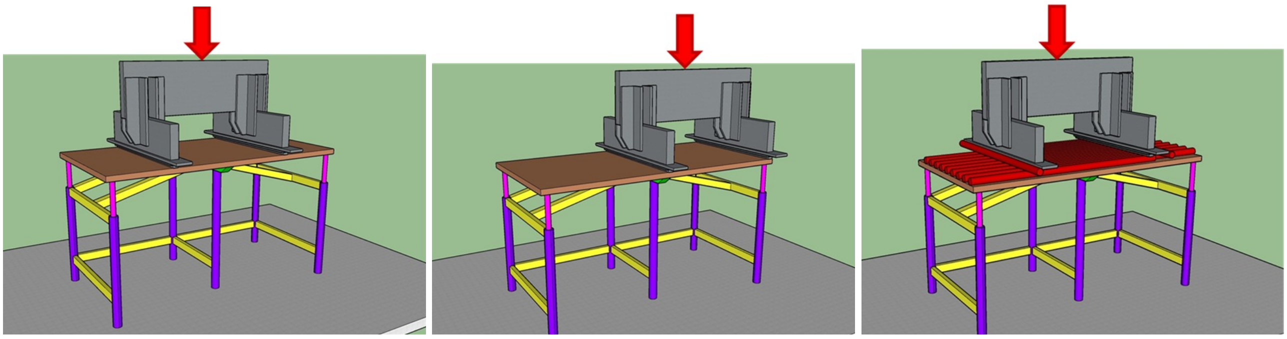
Figure 1: Compression (static) testing Set-up on a universal testing machine (UTM)

3.2. Applied Loading and Test Units

A total of five tests were conducted on two different desk sizes (3 secondary/high school desks and 2 primary/elementary school desks) and using three loading scenarios (See Table 1 and Figure 2). The secondary school desk size is the same as previous tests conducted in Italy and Bhutan. A new and smaller desk size intended for primary school children was also tested. Three loading scenarios were tested on the EQ desks: two-point concentric loading, two-point eccentric loading, and uniform loading. The two-point concentric load is intended to simulate loading that will result in the most damage to the plywood desktop. The two-point eccentric loading is intended to simulate off centre loading. The uniform loading is intended to simulate a very large piece of debris on the full desk. The uniform loading was achieved by applying a two-point concentric load to the top of eighteen #10 rebar welded together and laid to cover the entire surface of the desktop.

Table 1: Compression (push) test descriptions

Name	Desk Size	Loading
HSN-1	Secondary Schhol	Two-Point Concentric
HSN-2	Secondary School	Two-Point Eccentric
HSN-3	Secondary Schhol	Uniform
HSN-4	Primary School	Uniform
HSN-5	Primary School	Two-Point Concentric



(a) Two-point concentric (b) Two-point eccentric (c) Uniform

Figure 2: Compression (push) test loading scenarios

3.3. Compression Testing Results Summary

Figure 3a compares the force-displacement plots of the three load scenarios on the secondary/high school sized desks (HSN1-3). All plots show an initial loading mechanism and a secondary loading mechanism. The two- point concentric load deformed the desk the most and dissipated the most total energy. The two-point eccentric and the uniform load had similar peak load, although these peaks did not occur at similar displacements. In addition, the two-point eccentric and the uniform load had similar peak displacements, however the test of the uniform loading scenario was stopped due to test apparatus constraints and testing safety reasons, and therefore the desk could potentially deform further than presented in the figure. Figure 3b compares the performance of the secondary school sized desks with the primary/elementary school sized desks (ESN1-2). Overall, the primary school desks performed in a very similar manner and engaged similar mechanism as the secondary school desks. The primary school desks supported an average of 18 KN greater total load, however it deformed an average of 5% less than the secondary school desks.

Table 2 summarizes the load, deformation, and energy dissipation capacity of each of the tests. The minimum values across all loading scenarios and desk sizes are shown in bold. This table indicates that the capacity of the EQ Desk is significantly dependent on how the load is applied to the desk.

4. Dynamic Shock Table Test

4.1. Experimental Test Set-up and Construction Details

Dynamic testing was conducted using a 3.6-meter by 6.0-meter shock table facility at the Institute of Engineering, Tribhuvan University, Nepal. The experimental assembly included a two-walled classroom mock-up constructed of 0.45-meter-thick unreinforced stone masonry walls with mud mortar (see Figure 4). The roof assembly consisted of timber beams, bamboo planks, mud fill, and slate shingles, with an estimated mass of 2,210 kilograms. Each wall contributed an additional 7,650 kilograms.

Six EQ Desks (three high/secondary school size and three elementary/primary size) were positioned throughout the shock table footprint. Four desks incorporated newly developed plywood side protection panels to assess their role in limiting debris entry. To simulate the mass of children, 20-liter plastic water containers were affixed under each desk using light-weight zip-ties. Two conventional school benches were also included to study their performance and influence on debris flow during collapse.

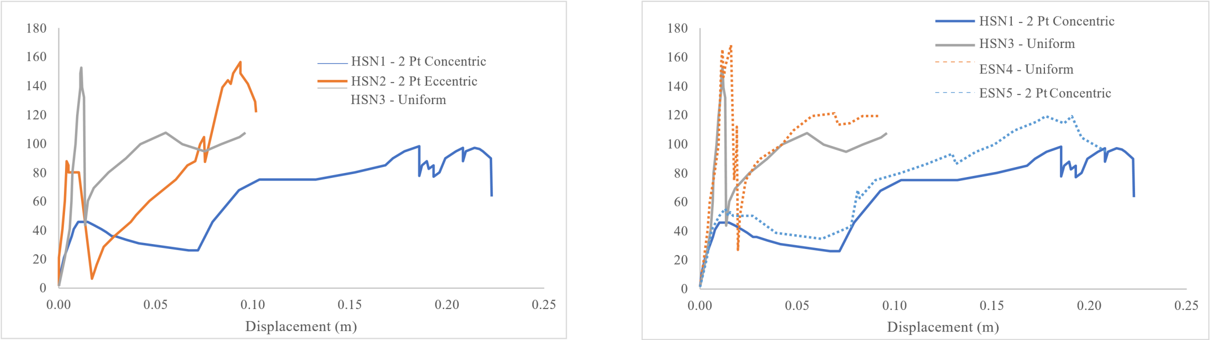
Dynamic loading was applied incrementally through a 2,070-kilogram pendulum. Seven sequential shocks were delivered, culminating in a 33-degree swing designed to induce full structural failure simultaneously. Accelerometers were installed on the shock table and walls to capture the acceleration history, supplemented by eight video cameras documenting collapse progression.

Additional details of the dynamic shock table tests are presented in a companion paper that focuses on the out-of-plane behavior of the unreinforced stone masonry walls (Veletzos et al., 2026).

4.2. Dynamic Shock Table Test Results and Observations

4.2.1 Collapse Progression

During initial pendulum swings of 5–10 degrees, the stone masonry walls sustained minor cracking without substantial permanent displacement. However, by the sixth shock, significant vertical separation developed between the wythes of the masonry walls. The final shock, applied at the maximum 33 degree pendulum angle, successfully triggered total collapse of both walls and the roof assembly.



(a) Comparison of lading type

(b) Comparison of desk size

Figure 3: Compression (push) test results

Table 2: Compression (push) test results summary

Desk	Description	Elastic Load (KN)	Ultimate (Peak) Load (kN)	Max Displacement (mm)*	Total Engergy (kJ)	Elastic Energy (kJ)
HSN-1	Secondary School Two-Point Concentric Load	45.7	98.2	223	14.2	0.51
HSN-2	Secondary School Two-Point Eccentric Load	80.0	157	102	7.86	0.28
HSN-3	Secondary School Uniform Load	149	153	96	8.73	0.64
ESN-4	Primary Schoo Uniform Load	159	168	92	7.05	0.68
ESN-5	Primary School Two-Point Concentric Load	55.5	119	209	15.6	0.46

* Maximum displacement is at the cener of load application. The maximum displacement of portions of the desk may be larger than this value

Video evidence confirmed that wall impacts preceded roof impacts, indicating sequential loading rather than a single uniform event. Figures 5, 6 and 7 show the collapse progressions of the walls onto the desks.

4.2.2 Loading on Desks

Desks adjacent to the walls experienced repeated vertical impacts on the desktop from stones falling from partial wall failure prior to the roof's collapse. Desks E and F, located nearest to the exterior wall, were subjected to pronounced lateral debris flows that displaced them approximately one meter across the shock table surface. Despite this movement, no desks overturned.

In contrast, desks positioned further within the mock-up were largely constrained by adjacent walls and desks, limiting lateral displacement. The sequence of collapse and debris accumulation on each desk was clearly visible in the high-speed video footage.

4.2.3 Damage and Debris Intrusion

Post-test inspection revealed only superficial damage to the EQ Desks (see Figure 8a). Cosmetic failures such as plywood edge delamination and minor dents were observed on desktops. Importantly, no desk structures collapsed or deformed to an extent that compromised the safety-zone beneath.

Debris accumulation beneath desks was markedly less in units equipped with side protection panels. In desks without side protection, water containers simulating children were sometimes displaced or toppled by the debris wave. Nevertheless, none were punctured or crushed, suggesting that debris velocity and mass were insufficient to create lethal conditions.

Traditional school benches adjacent to desks absorbed significant impact and exhibited permanent deformation (see Figure 8b), indicating their partial effectiveness in moderating debris flow.

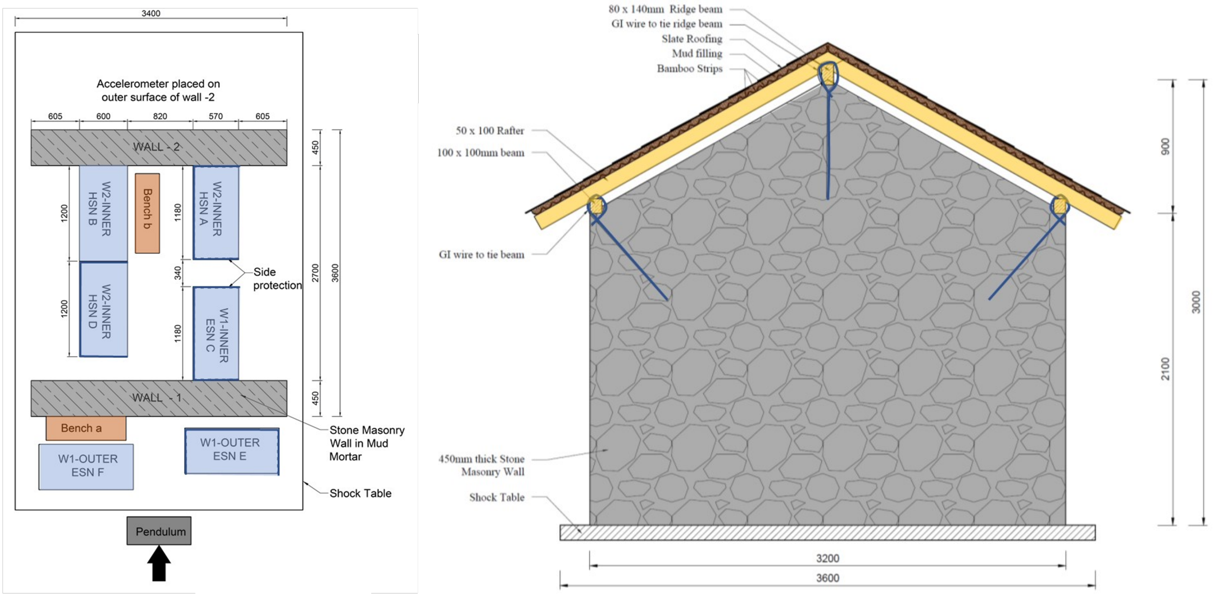


Figure 4: Building mock-up details (note: dimensions are in mm)

Figure 5: Collapse progression of wall 2 onto desks A and B (secondary school)

5. Demand Estimates on Desks

This section discusses approaches to estimating the demands on the desks. Over the years, a few engineering groups developed demand estimates for the EQ Desks, and summaries of these estimates were shared with the research team. These estimates use two separate approaches to account for the dynamic behavior of a structure collapsing on top of the desk: (1) an impact load approach, and (2) an energy approach. The impact load approach is an elastic design methodology and should be compared against an elastic load capacity[1] of the desk. This approach amplifies the dead weight of falling debris with a scale factor to account for dynamic amplification. A commonly used factor is 2.0 although this value can vary greatly depending on the type of dynamic amplification is being considered. This approach does not consider the deformability of the desk to absorb impacts through permanent deformations. The

Figure 6: Collapse progression of wall 1 onto desk C (primary school) and desk D (secondary school)

Figure 7: Collapse progression of wall 1 onto desks E and F (primary school)

energy approach is an inelastic design methodology and compares the energy demands with the energy capacity of the EQ Desks. This approach allows for consideration of the damage absorption features of the desks. The calculations generally compute the energy demand using the potential energy equation (i.e. mass x gravity x height of fall).

Both of these approaches require an estimate of the mass that is falling on the desk. The observations from the shock table tests indicate that only a portion of the walls fall on the desks, and the impacts of debris from the wall are not

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[1] The elastic load capacity is often defined as the yield load which is the loading on the desk that causes initial yielding and indicates that permanent deformations will occur if additional loading is added.

(a) Desk C (foreground) with desk A at right and desk D in the cener background

(b) Bench 'a' for Desk F

Figure 8: Comparison of desk and bench damage

synchronous with the impact from the roof, as the roof collapses after the walls fail. In addition, it appears that the roof impacts are larger than the wall impacts. The total roof mass (including timber beam, bamboo planking, mud filling, and slate shingles) was estimated to be 2210 kg (22.0 kN). The shock table test results show that the roof mass falls on the desks after the rubble of the walls. If we assume the total roof mass is distributed evenly across the surface area of the desktops and the original wall footprint, we determine that each desk will feel approximately 10% of the total roof mass (i.e. 221 kg or 2.2 kN on each desk). For comparison with the wall mass, if we assume a tributary volume of wall mass divides into 10 separate impact pieces, the impact mass from the wall is estimated to be 73 kg (0.71 kN)[2]or approximately 33% of the estimated roof mass. In addition, the roof masses fall from a height estimated to be 2 m above the top of the desk, while the wall masses typically fall from a height of approximately half this height. Consequently, the roof masses are estimated to impact the desktops with approximately six times the potential energy as the wall masses.

Figure 9a compares the impact load demand estimate with the EQ Desk capacities on the force- displacement plots for a visual comparison. The impact load demand is small compared to the minimum elastic load capacity and aligns with the minimal damage observed from the shock table tests. Figure 9b compares the "free-fall" energy demand, estimated to be 4.3 kJ with the force-displacement plots to visualize the comparison with the EQ Desk capacities. The "free-fall" energy demand (shown as the shaded area under each curve in Figure 9b), is very large compared to the minimum elastic energy capacity of 0.28 kJ and would suggest significant observable damage. However, this level of damage was not observed. The difference is likely due to the inaccurate assumption that the roof is in pure free-fall. The results of the shock table test clearly show that the roof is not in pure free-fall, and the energy demand estimates should be reduced significantly to align with the observed damage. A value of 2%-6% of the "free-fall" potential energy would align with the observed damage for this type of building construction.

Table 3 compares the estimated demands (D) from the two approaches with the elastic capacities (C) from the compression (push) tests. The D/C for the Impact Load approach is 0.09 which is quite low and suggests the impact factor of 2 used in this approach may be too small. The "Free-Fall" energy demands from the Energy approach is compared to the minimum elastic energy capacity from the compression (push) tests. The D/C ratio for the Energy approach is 15.5 and indicates the desk are expected to have significant damage, but this level of damage was not observed in the tests and clearly indicate that this demand approach is not correct.

In summary, neither approach is ideal in estimating the demands on the EQ Desk and both approaches have deficiencies. The elastic design approach does not utilize the non-linear capabilities of the various design features of the EQ Desk. Using an elastic design approach will result in desk designs that are much stronger than needed and potentially more expensive than necessary. The energy approach assumes that the full roof mass is in "free fall", however the shock table tests indicate that this assumption is not accurate and this approach significantly over-estimates the energy demands on the EQ Desks. It is possible to approximate a reduction factor on the "free-fall" energy to estimate the energy demands on the desk, however this is difficulty to do accurately based on a single shock table

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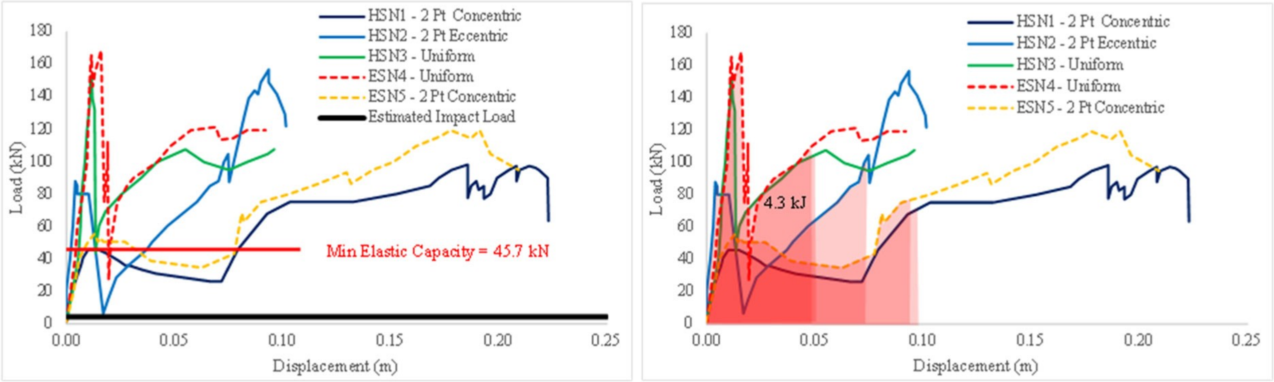
[2] The tributary volume of wall was calculated as the desktop area times the full width of the wall (i.e. 1.2m x 0.6m x .45m = 0.324m^3). This total volume was then divided by 10 with the assumption that the wall breaks as it falls and does not impact the desk as a single mass, but rather several smaller masses that impact in rapid succession. The unit weight of the wall was assumed to be 22 kN/m^3



(a) Impact load approach

(b) Energy approach

Figure 9: Estimated demands vs capacities

Table 3: Demand and capacity comparison for impact load and energy approaches

Approach	Trib. Roof Mass (kg/desk)	Impact Factor	Free-fall Height	Demand	Capacity	D/C	Comment
Impact Load	221	2	NA	4.34 kN	45.7 kN	0.09	Min elastic load capacity
Energy (Elastic)	221	NA	2.0 m	4.34 kJ	0.28 kJ	15.5	“Free-fall” energy vs. min elastic energy capacity

test. Other building types may not behave exactly as this mock-up behaved, so there will be significant uncertainty in this reduction factor.

6. Conclusion

Based on the compression tests and the shock table test, we can draw the following conclusions regarding the performance of the EQ Desks:

- The capacity of the EQ Desk dependents on the how the load is applied to the desk.
- The desks felt wall and roof impacts separately during the shock table test. Similarly, wall impact loading on the desks does not occur simultaneously, but rather in “pieces.”
- Vertical demands on the desks are governed by roof mass, when a heavy roof is present.
- EQ Desks performed very well during the shock table test, with only cosmetic damage to the plywood desktop and edging while maintaining the full “safety-zone” below the desks.
- Vertical demands on the top of the desk from the shock table test were below the minimum elastic load capacity of 45.7 kN on each desk and also below minimum elastic energy of 0.28 kJ on each desk.
- A lateral debris wave from the wall pushed desks that were not confined by walls or other desks, but the desks did not topple.
- Desks with side protection panels showed reduced debris entering the safety-zone, though they experienced more lateral displacement, possibly due to acting as a sail in the debris wave.

In summary, the dynamic shock table test demonstrates that Earthquake Desks manufactured in Nepal are highly effective in preserving a survivable safety-zone under conditions simulating the collapse of heavy masonry walls and roof structures. All desks maintained their integrity, and only demonstrated cosmetic damage. Overall, the experiments validate the abality of EQ Desks to protect occupants in single-story stone masonry buildings. Future evaluations are needed to confirm performance in multi-story or reinforced concrete buildings.

7. Recommendations

Based on these static and dynamic test results, the following recommendations are proposed:

- Conduct additional compression test to confirm consistency in manufacturing and validate reproducibility of performance.

- Standardize inclusion of side protection panes, for desks positioned adjacent to walls.
- Impact mass should be computed based on a tributary roof mass (mtrib) on each desk[3].
- Update elastic impact load approaches by increasing dynamic amplification factors to 4-5 to better approximate collapse impact loads and align with observed damage.
- In inelastic energy assessments, apply reduction factors to energy estimates, targeting 2-6% of calculated ”free-fall” energy based on a tributary area of room mass.
- Extend testing to other building typologies, including reinforced concrete frames and multi-story structures, to confirm applicability across broader contexts.
- Consider pairing EQ Desks with benches to further mitigate debris intrusion.

References

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[3] mtrib = mtotal roof x (Adesk/Atotal). mtotal roof is the approximate mass of the roof of the full building. Adesk is the surface area of the top of the desk. Atotal is the total area of the desks and the walls (=n x Adesk + Awall), where n is the number of desks in the building. Awall is the total footprint area (i.e. cross section area) of stone walls in the building

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