Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 03 , March - 2026

Experimental Investigation and Behavior of Various Shear Walls Under Lateral Loads

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Abstract: Shear walls offer an economic means to provide lateral load resistance in multi-storey buildings. The seismic behavior of shear walls, modes of failure, and the factors influencing their structural response are discussed. Expressions are developed to estimate the flexural strength of slender rectangular shear wall sections with uniformly distributed vertical reinforcement. These expressions are consistent with the provisions of IS: 456-2000. The axial load-moment interaction diagram for the section is also developed from these expressions. An alternative numerical method is also defined for the same. Although various research studies have been conducted on the design of reinforced concrete shear walls, these studies were limited by the laboratory capacity. This led to inability of testing walls with their full height for high to mid-rise shear walls.

Reinforced cement concrete (RCC) shear walls are used in buildings to resist lateral forces due to earthquakes wind pressure. They are usually provided between column lines, lift wells, in stair wells, and in shafts that house other utilities. Shear walls provide lateral load resistance by transferring the wind or seismic loads to the foundation. They also impart lateral stiffness to the system and carry gravity loads. A well-designed system of shear walls in a building frame improves its seismic performance significantly. This is evident from studies on the comparative behavior of building frames with shear walls in past earthquakes framed buildings.

Keywords - Shear wall, lateral forces, seismic loads, failure.

1. INTRODUCTION

As per IS: 456-2000 incorporates some provisions for design of reinforced concrete walls. However, no explicit provisions are given for calculating the flexural strength of shear wall sections which are quite different from beam sections as they have reinforcement distributed along their whole length in plan. Extensive experimentation has been carried out abroad to assess the strength and behavior of RC shear walls under monotonic and reversed cyclic loading. In reinforced concrete buildings, especially those buildings located in seismic regions, shear walls are essential for resisting lateral forces and maintaining overall stability.

These walls are typically provided with boundary elements at their edges, where longitudinal reinforcement is designed in varying percentages to handle tension and compression.

Depending on the height-to-width ratio (H/B), a shear wall may behave as a slender wall, a squat wall, or a combination of the two. Slender shear walls usually have a height-to-width ratio greater than 2. They behave like a vertical slender cantilever beam. The primary mode of deformation is bending; shear deformations are small and can be neglected. Flexural strength usually governs the design of such walls.

1.1 Literature Review

A several researchers have investigated the role of boundary elements in shear wall performance, particularly under lateral and seismic loads. A study by Kumar and colleagues (2023) analyzed squat shear walls subjected to high axial and cyclic lateral loads using both experimental and finite element analysis methods. The study outlined that poor boundary reinforcement detailing led to concrete crushing and edge instability, especially under elevated axial loads, underscoring the risk of failure when detailing is

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ISSN: 2278-0181
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misaligned. In another experimental study, Hassan et al. (2022) tested small-scale shear wall specimens under lateral loading. The results observed that the tested specimens lacking properly detailed boundary elements, exhibited premature cracking and reduced ductility, while those with boundary elements showed better energy dissipation and delayed failure, highlighting the importance of field accuracy in reinforcement placement. Mohammad et al. (2022) employed ensemble deep learning models to classify failure modes in reinforced concrete shear walls using parameters such as boundary element area and wall aspect ratio. Their findings showed that inadequate boundary element reinforcement can shift the failure mode from ductile flexural failure to brittle shear or sliding failure, emphasizing the critical role of boundary design in seismic zones. is study aimed to examine and determine the efficiency of the ensemble neural networks to predict the failure mechanism of the RCSWs. The strongest model for predicting the failure mode of the RCSWs is determined by evaluating ensemble deep neural network models: model averaging, weighted average, and integrated stacking. Ensemble models are based on 5 neural network sub-models.

2. METHODOLOGY

To analysis the impact of boundary element reinforcement errors, a G+13+ terrace reinforced concrete building was modeled using ETABS software. The structure was analyzed under seismic loading conditions, considering a response reduction factor (R) of 5 as per IS 1893 provisions for ductile detailing, and located in Seismic Zone IV.

The design was carried out using the Simplified Center and Torsion (C&T) method available in ETABS. This method automatically assigns varying Modal Participating Mass Ratios values and tensional irregularities to each boundary element based on the wall's position, loading demand, mass ratios, joint displacements, storey drift, mass displacements, storey displacements, maximum storey displacements. As a result, each shear wall in the building received different Ast values on its two ends, reflecting a realistic design approach. A summary table Modal Participating Mass Ratios for each shear wall and their corresponding boundary zones is attached below:

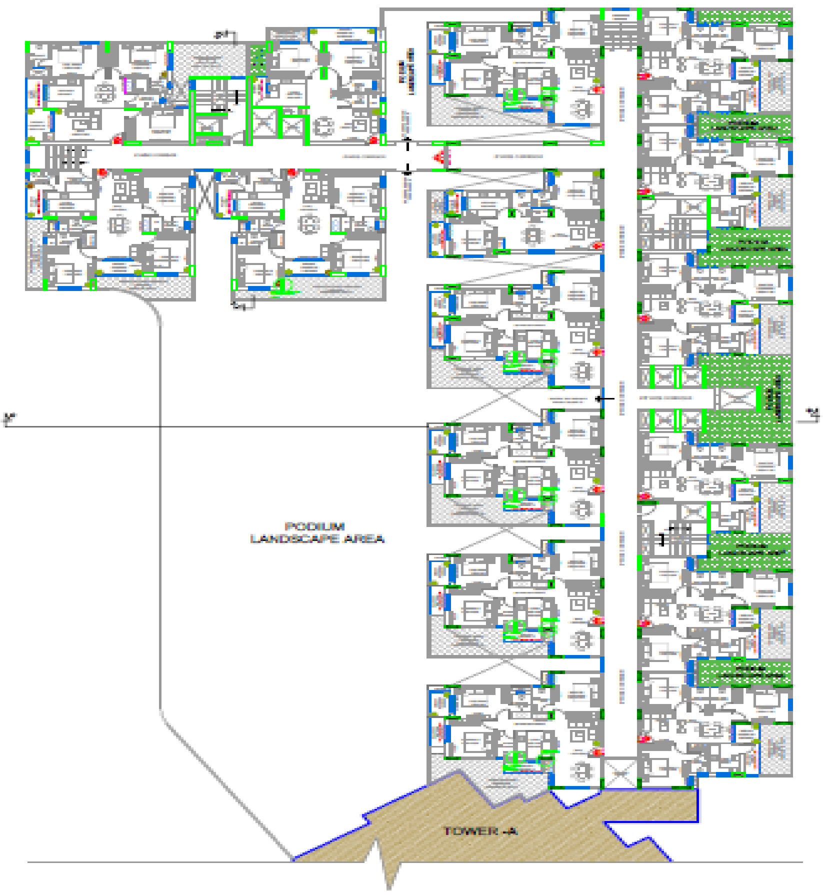

Figure-1: Floor plan

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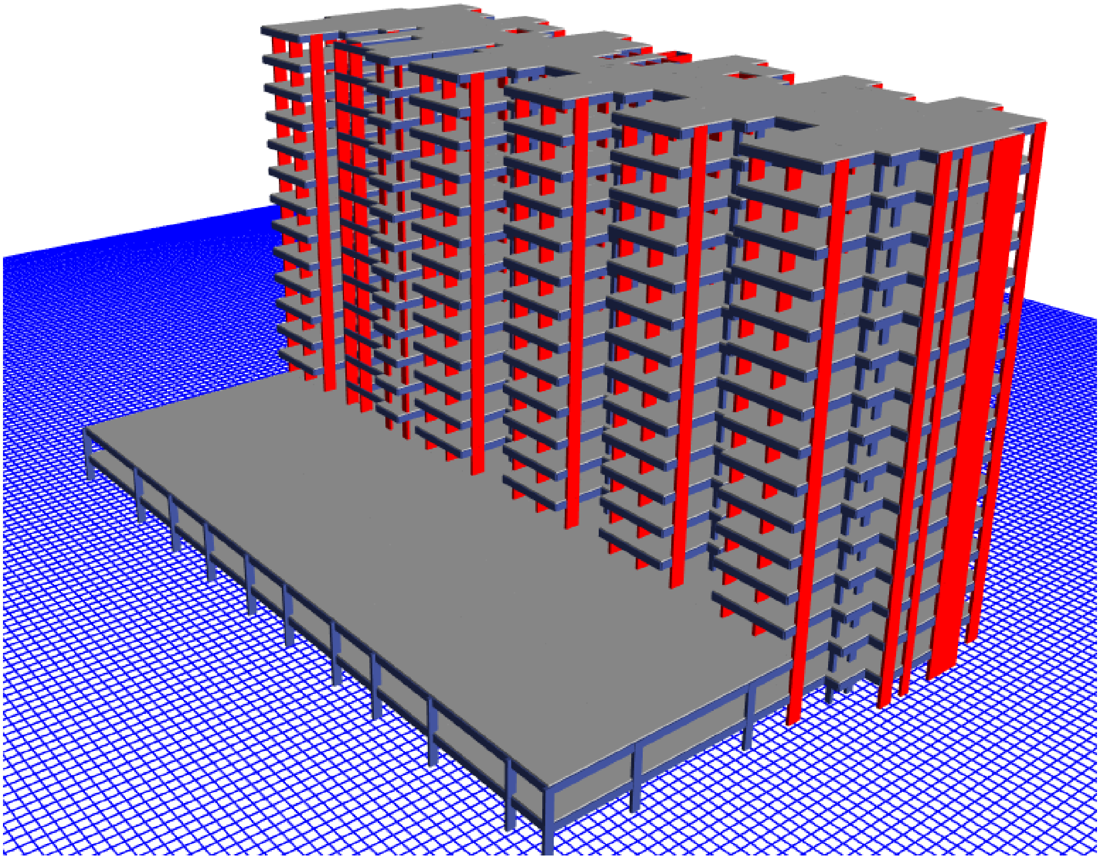

Figure-2: Building Model

TABLE-1: Modal Participating Mass Ratios														
Case	**Mode**	**Period**	**UX**	**UY**	**UZ**	**SumUX**	**SumUY**	**SumUZ**	**RX**	**RY**	**RZ**	**SumRX**	**SumRY**	**SumRZ**
		sec												
Modal	1	1.818	0.00	0.67	0.00	0.00	0.67	0.00	0.09	0.00	0.00	0.09	0.00	0.00
Modal	2	1.731	0.58	0.00	0.00	0.58	0.67	0.00	0.00	0.22	0.05	0.09	0.22	0.05
Modal	3	1.484	0.05	0.01	0.00	0.64	0.68	0.00	0.00	0.02	0.56	0.09	0.24	0.61
Modal	4	0.79	0.00	0.00	0.00	0.64	0.68	0.00	0.00	0.00	0.00	0.09	0.24	0.61
Modal	5	0.553	0.00	0.13	0.00	0.64	0.81	0.00	0.08	0.00	0.00	0.17	0.24	0.62
Modal	6	0.491	0.13	0.00	0.00	0.77	0.81	0.00	0.00	0.14	0.01	0.17	0.38	0.63
Modal	7	0.438	0.00	0.00	0.00	0.77	0.81	0.00	0.00	0.00	0.12	0.18	0.38	0.75
Modal	8	0.375	0.02	0.00	0.00	0.80	0.81	0.00	0.00	0.03	0.02	0.18	0.40	0.77
Modal	9	0.361	0.00	0.00	0.00	0.80	0.81	0.00	0.00	0.00	0.00	0.18	0.40	0.77
Modal	10	0.306	0.00	0.02	0.00	0.80	0.83	0.00	0.01	0.00	0.00	0.19	0.40	0.77
Modal	11	0.302	0.00	0.05	0.00	0.80	0.89	0.00	0.02	0.00	0.01	0.20	0.40	0.78
Modal	12	0.258	0.01	0.00	0.00	0.81	0.89	0.00	0.00	0.01	0.00	0.20	0.42	0.79
Modal	13	0.25	0.01	0.00	0.01	0.81	0.89	0.01	0.01	0.00	0.00	0.21	0.42	0.79
Modal	14	0.24	0.04	0.00	0.00	0.85	0.90	0.01	0.00	0.04	0.00	0.21	0.46	0.79
Modal	15	0.224	0.00	0.03	0.00	0.86	0.92	0.01	0.01	0.00	0.01	0.23	0.46	0.80
Modal	16	0.206	0.00	0.01	0.02	0.86	0.93	0.03	0.01	0.00	0.00	0.23	0.46	0.80
Modal	17	0.194	0.01	0.00	0.07	0.87	0.93	0.10	0.00	0.04	0.00	0.24	0.50	0.80
Modal	18	0.166	0.01	0.00	0.35	0.88	0.93	0.44	0.00	0.01	0.00	0.24	0.51	0.81
Modal	19	0.154	0.04	0.00	0.08	0.92	0.94	0.52	0.00	0.05	0.00	0.24	0.55	0.81

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Modal	20	0.137	0.01	0.02	0.00	0.93	0.96	0.53	0.02	0.01	0.01	0.25	0.57	0.81
Modal	21	0.119	0.00	0.00	0.20	0.93	0.96	0.73	0.01	0.00	0.00	0.26	0.57	0.81
Modal	22	0.08	0.02	0.02	0.00	0.95	0.98	0.73	0.01	0.03	0.00	0.27	0.61	0.81
Modal	23	0.07	0.03	0.01	0.01	0.98	0.99	0.74	0.00	0.04	0.00	0.27	0.65	0.81
Modal	24	0.055	0.00	0.00	0.20	0.98	0.99	0.93	0.00	0.02	0.00	0.27	0.67	0.81

TABLE-2a: Joint Displacements

Story	Label	Output Case	Ux	Uy	AVG	MAX/AVG	
			mm	mm			check
TERRACE	3401	SPECX	71.825	4.117	57.12	1.259	ok
TERRACE	3404	SPECX	71.901	6.451			
TERRACE	3725	SPECX	42.372	15.784			
TERRACE	3753	SPECX	42.398	13.710			

TABLE-2b: Joint Displacements

Story	Label	Output Case	Ux	Uy	AVG	MAX/AVG	
			mm	mm			check
TERRACE	3401	SPECY	10.614	36.485	11.021	1.038	ok
TERRACE	3404	SPECY	10.625	35.157			
TERRACE	3725	SPECY	11.404	35.866			
TERRACE	3753	SPECY	11.439	37.653			

TABLE-3a: Story Drifts

Story	Output Case	Direction	Drift	
TERRACE	SPECX	X	0.00140	OK
Story13	SPECX	X	0.00147	OK
Story12	SPECX	X	0.00159	OK
Story11	SPECX	X	0.00171	OK
Story10	SPECX	X	0.00181	OK
Story9	SPECX	X	0.00190	OK
Story8	SPECX	X	0.00196	OK
Story7	SPECX	X	0.00199	OK
Story6	SPECX	X	0.00200	OK
Story5	SPECX	X	0.00196	OK
Story4	SPECX	X	0.00188	OK
Story3	SPECX	X	0.00172	OK
Story2	SPECX	X	0.00146	OK
STORY1	SPECX	X	0.00106	OK
STILT-2	SPECX	X	0.00046	OK

TABLE-3b: Story Drifts

Story	Output Case	Direction	Drift	
TERRACE	SPECY	Y	0.00078	OK
Story13	SPECY	Y	0.00082	OK
Story12	SPECY	Y	0.00094	OK

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Story11	SPECY	Y	0.00101	OK
Story10	SPECY	Y	0.00105	OK
Story9	SPECY	Y	0.00108	OK
Story8	SPECY	Y	0.00112	OK
Story7	SPECY	Y	0.00114	OK
Story6	SPECY	Y	0.00115	OK
Story5	SPECY	Y	0.00116	OK
Story4	SPECY	Y	0.00117	OK
Story3	SPECY	Y	0.00117	OK
Story2	SPECY	Y	0.00109	OK
STORY1	SPECY	Y	0.00074	OK
STILT-2	SPECY	Y	0.00045	OK

Diaphragm Displacements:

TABLE-4: Diaphragm Center of Mass Displacements

Story	Load Case/Combo	UX	UY	Permissible Limit:		
		mm	mm	mm		
TERRACE	SPECX	52.429	2.995	H/250	179.8	OK
TERRACE	SPECY	2.539	35.525			OK

Story Stiffness Table

TABLE-5a: Story Stiffness

Story	Output Case	Shear X	Drift X	Stiff X		
		kN	m	kN/m		
TERRACE	EQX	2016.0013	3.675	548499.7	-	
Story13	EQX	3954.5952	3.855	1025842	1.87	OK
Story12	EQX	5624.2869	4.076	1379930	1.35	OK
Story11	EQX	7046.6785	4.29	1642450	1.19	OK
Story10	EQX	8241.5803	4.468	1844545	1.12	OK
Story9	EQX	9228.8028	4.594	2008989	1.09	OK
Story8	EQX	10028.1563	4.655	2154383	1.07	OK
Story7	EQX	10659.4514	4.642	2296268	1.07	OK
Story6	EQX	11142.4985	4.554	2446593	1.07	OK
Story5	EQX	11497.1079	4.376	2627290	1.07	OK
Story4	EQX	11743.0902	4.118	2851455	1.09	OK
Story3	EQX	11900.2557	3.748	3175308	1.11	OK
Story2	EQX	11988.4148	3.137	3821231	1.20	OK
STORY1	EQX	12059.4382	2.188	5511927	1.44	OK
STILT-2	EQX	12075.5114	0.853	14163550	2.57	OK

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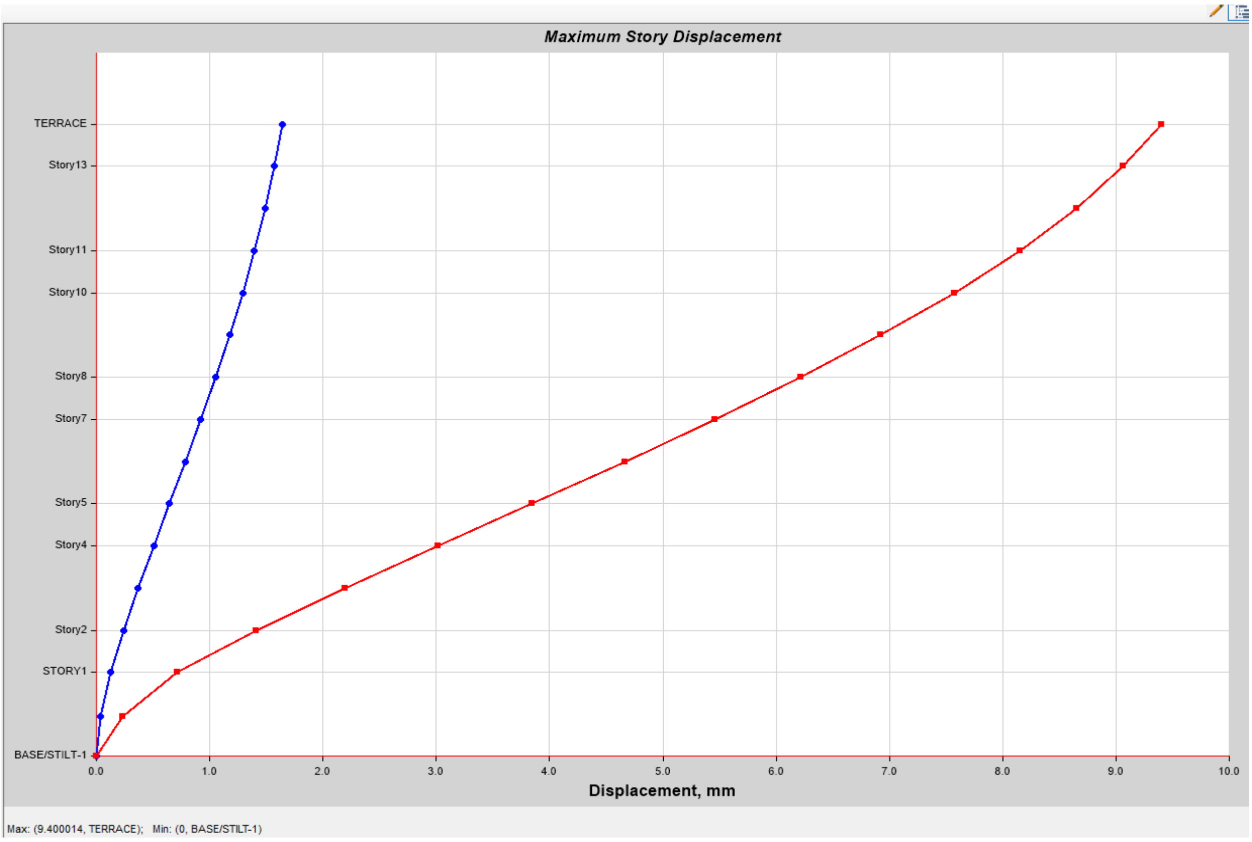
TABLE-5b: Story Stiffness						
Story	**Output Case**	**Shear Y**	**Drift Y**	**Stiff Y**		
		kN	m	kN/m		
20TH FLOOR	EQY	1295.2088	2.159	599783	-	
PROVISION 2	EQY	2540.686	2.406	1055904	1.76	OK
PROVISION 1	EQY	3613.4033	2.651	1363241	1.29	OK
19TH FLOOR	EQY	4527.239	2.869	1578182	1.16	OK
18TH FLOOR	EQY	5294.9207	3.099	1708424	1.08	OK
17TH FLOOR	EQY	5929.1758	3.302	1795767	1.05	OK
16TH FLOOR	EQY	6442.7319	3.442	1871543	1.04	OK
15TH FLOOR	EQY	6848.3164	3.519	1945861	1.04	OK
14TH FLOOR	EQY	7158.6569	3.528	2029062	1.04	OK
13TH FLOOR	EQY	7386.4808	3.47	2128583	1.05	OK
12TH FLOOR	EQY	7544.5156	3.338	2260241	1.06	OK
11TH FLOOR	EQY	7645.4888	3.118	2451814	1.08	OK
10TH FLOOR	EQY	7702.1279	2.678	2876231	1.17	OK
9TH FLOOR	EQY	7747.7579	1.946	3980718	1.38	OK
8TH FLOOR	EQY	7758.0843	0.728	10655073	2.68	OK



Graph: Displacement vs storey

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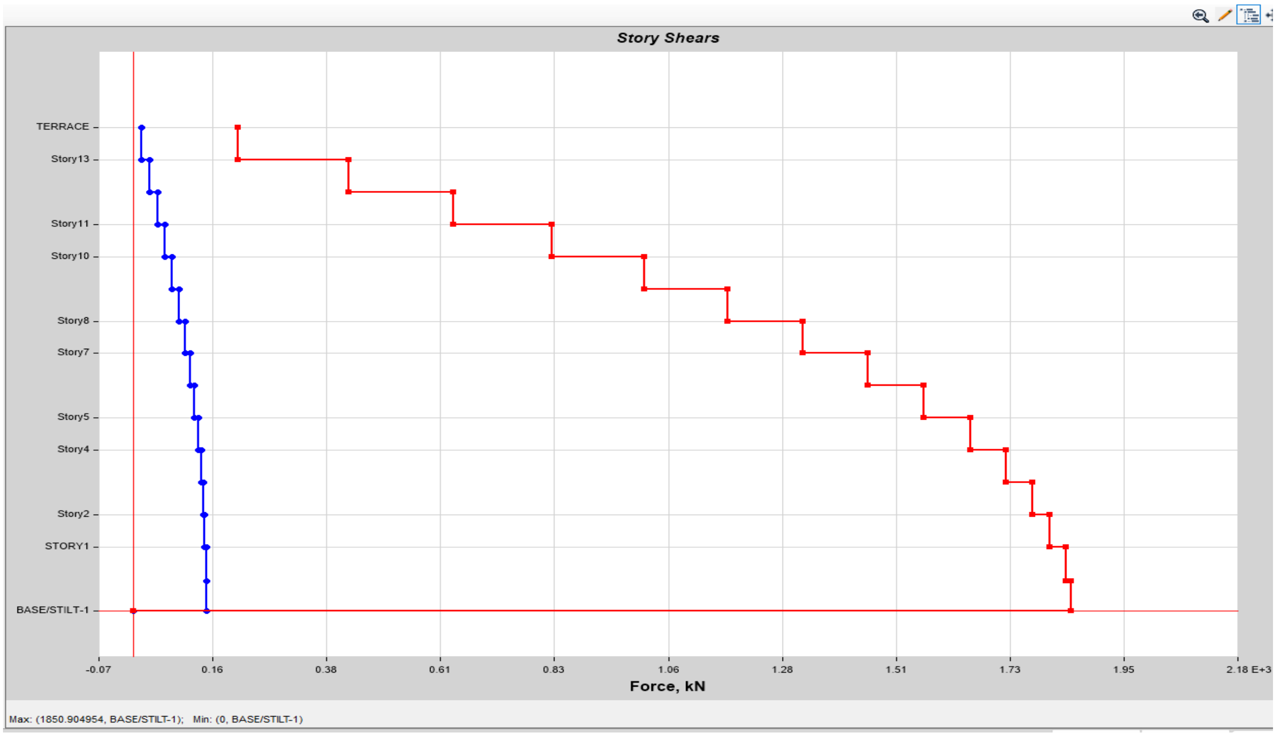

3. RESULTS

The initial design, as shown in Table 1, provides a precise distribution of mass ratios in each shear wall, with varying values assigned to the two boundary elements based on their respective force demands. This ensures structural joint displacements and compliance with code requirements. However, in situations where a construction error leads to the reversal or misplacement of these reinforcements at the boundary zones, the shear wall develops a non-uniform reinforcement condition—creating one under-reinforced edge and one over-reinforced edge. This discrepancy disrupts the intended moment resistance capacity of the wall and can result in premature failure under lateral or seismic forces. The wall is most vulnerable on the side originally designed to resist higher tension forces,. The table below summarizes the joint displacement and storey drift between the two boundary elements for each shear wall and identifies the corresponding failure stage likely to occur if such a misplacement happens during construction.

4. CONCLUSION

Reinforcement in structural element plays an important role. While accurate design is essential, it alone is not sufficient the correct execution of reinforcement detailing on-site is equally, if not more, important. Specifically, in the case of longitudinal reinforcement errors in shear wall boundary elements, where reinforcement with different joint displacement values changed, the wall becomes structurally compromised. Such an error can cause the wall to fail at a critical stage of loading.

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