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REINFORCED CONCRETE WALL RESPONSE UNDER UNI- AND BI-DIRECTIONAL LOADING

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Abstract

During an earthquake, structures are subjected to both horizontal and vertical shaking. Most structures are rather insensitive to variations in the vertical acceleration history and primary considerations are given to the impact of the horizontal shaking on the behavior of structures. In the laboratory, however, most component tests are carried out under uni-directional horizontal loading to simulate earthquake effects rather than bi-directional loading. For example, biaxial loading tests of reinforced concrete (RC) walls constitute less than 0.5% of all quasi-static cyclic tests that have been conducted. Bi-directional tests require larger and more complex test setups than uni-directional tests and therefore should only be pursued if they provide insights and results that cannot be obtained from uni-directional tests. To investigate the influence of bi-directional loading on RC wall performance, this paper reviews results from quasi-static cyclic tests on RC walls that are reported in the literature. Results from uni-directional tests are compared to results from bi-directional tests for walls of different cross sections including rectangular walls, T-shaped walls, and U-shaped walls. The available test data are analyzed with regard to the influence of the loading history on stiffness, strength, deformation capacity and failure mode. Walls with T-shaped and U-shaped cross sections are designed to carry loads in both horizontal directions and thus consideration of the impact of bi-directional loading on behavior should be considered. However, it is also shown that the displacement capacity of walls with rectangular cross sections is typically reduced by 20 to 30% due to bi-directional loading. Further analysis of the test data indicates that the bi-directional loading protocol selected might impact wall strength and stiffness of the test specimen. Based on these findings, future research needs with regard to the response of RC walls subjected to bi-directional loading are provided.

Keywords: Reinforced concrete walls, uni-directional loading, bi-directional loading, quasi-static cyclic tests, stiffness, strength capacity, deformation capacity

1 Introduction

Reinforced concrete (RC) walls provide lateral stiffness and strength to many mid- to high-rise buildings. A variety of wall geometries are used, including planar walls with rectangular, barbell-shaped (columns at both ends), which are designed to carry shear forces primarily in one horizontal direction only, and non-planar walls, which are designed to carry shear forces in two principle directions (e.g., walls with L-, T-, I-, U- or C-shaped cross sections). Shake table tests are the closest representation of earthquake loading in a laboratory environment; however, a majority of tests are conducted under quasi-static, reversed cyclic loading because the required testing equipment is less expensive, and thus more widely available, and wall behavior can be assessed under increasing amplitudes of load and/or displacement to assess the evolution of damage as demands are increased. In addition, due to the slow loading rate, it is possible to assess responses in real time and repair broken sensors or faulty wires, use more and cheaper sensors, and to provide more detailed documentation (e.g., photos, crack patterns, crack widths). For these reasons, quasi-static, reversed cyclic testing is the principal source of experimental data for structural testing, particularly when testing is being performed on structural elements (as opposed to a structural system). These observations apply to RC walls, with hundreds of quasi-static tests reported in the literature, as summarized in various databases, such as the NEES shear wall database [1], SERIES shear wall database [2], and Gulec and Whittaker database on squat walls [3].

The vast majority of quasi-static cyclic tests reported in the literature are planar walls subjected to uni-directional loading parallel to the wall web. Bi-directional wall tests are rather scarce, with a majority conducted after 2005, and these tests have not been systematically studied or assembled into a publically available database. However, observations of wall damage following the 2010 and 2011 earthquakes in Chile and New Zealand suggest that bi-directional loading may have played an important role in the degree and type of damage observed [4]–[6]. Damage was reported in many walls with complex geometries (i.e., non-planar walls), and included damage that produced significant out-of-plane displacements (or lateral instabilities relative to in-plane loading). The extent to which bi-directional loading impacted the observed damage has not been systematically assessed [7]. In total there are approximately 50 quasi-static cyclic tests of non-planar walls; approximately 20% of these were subjected to bi-directional loading. Given that bi-directional tests are more complex (expensive) than uni-directional tests, a thorough evaluation of the existing tests is needed to assess key attributes (e.g., geometric, material, or loading protocol) where behaviour under bi-directional loading differs, and in which aspects results from uni-directional tests differ from those of bi-directional tests.

The objective of this paper is to address the impacts of bi-directional loading on wall responses by reviewing existing experimental evidence for both planar and non-planar walls. The work is part of an ongoing effort of a working group of the NSF SAVI Wall Institute (http://apedneault4.wix.com/wall-institute) on quantifying the effect of bi-directional loading on wall performance. The paper concludes with a summary of our findings and a discussion of future research needs.

2 Effect of Bi-directional Loading on Planar Walls

Three quasi-static cyclic test campaigns on planar walls with rectangular or nearly rectangular wall sections subjected to bi-directional loading are documented in the literature. These are the campaigns by Tatsuya [8], Kabeyasawa et al. [9] and Almeida et al. [10]. Tatsuya [8] tested in total five walls, one under uni-directional loading and four under bi-directional loading. Due to the relatively high axial load ratio of n=0.13-0.17 all walls failed due to web crushing. The displacement capacity of the bi-directional test was 75% of the uni-directional test, which was attributed to the increased compressive strains and associated concrete spalling, at wall edges due to bi-directional loading. The stiffness and peak load were not affected significantly by bi-directional loading protocol used.

Kabeyasawa et al. [9] tested four pairs of walls, each pair consisting of walls with rectangular- and barbell-shaped cross sections, under uni- and bi-directional loading. As in Tatsuya's study, the test specimens were subjected to significant axial load ratios of n=0.08-0.12. In all tests, yielding of boundary longitudinal reinforcement was observed, followed by crushing failures at the wall base for pairs WA and WB, and sliding failures at the base for pairs WC and WD. For all tests, as observed by Tatsuya [8], bi-directional loading led to roughly a 20% reduction of the displacement capacity (except for test WD2D, where the actual loading deviated significantly from the intended loading protocol). The reduction in displacement capacity under bi-directional loading was linked to significantly larger crack widths and an earlier onset of concrete crushing for WA2D and WB2D; for WC2D and WD2D increased local deformations (larger cracks, localized concrete spalling) when compared to WC1D and WD1D was not observed [9] and no explanation was offered to explain the reduced displacement capacity.

The wall tests at EPFL by Almeida et al. differed from those described in [8] and [9] in several regards [10]: 1) The walls featured a single layer of vertical web reinforcement, whereas others had two layers of vertical web reinforcement. 2) They were subjected to significantly lower axial loads of n=0.03-0.04 (the difference results from different concrete strengths of the test units). 3) The in-plane and out-of-plane displacements at the top of the wall were controlled to be equal. 4) Crushing failure was for both walls initiated through out-of-plane instability [11].

For all planar wall tests, lateral stiffness and peak lateral strength was not significantly affected by the out-of-plane displacements (Fig. 1 and Fig. 2). The wall widths were small compared to the wall length; therefore, the out-of-plane displacement caused only small additional strain demands. These additional strain demands were, however, sufficient to trigger failure at a lower displacement (Table 1). In Table 1, drift capacity was defined as the drift for which the force capacity had dropped to 80% of the peak force. Results presented in Table 1 show that, for the five pairs that enable direct comparisons, bi-directional loading reduced the in-plane drift capacity by 16-25%; with an average reduction of 20%. This very limited data set seems to suggest that deformation capacities derived from uni-directional tests may need to be reduced to account for bi-directional loading. The data set seems, however, too limited and inconsistent to draw any conclusions that go much beyond such a qualitative statement.

Table 1 – Drift capacities obtained from planar wall tests subjected to uni- and bi-directional loading.

Test campaign	Uni-directional test Test unit & $\delta_{u,uni}$	Bi-directional test Test unit & $\delta_{u,bi}$	Ratio of drift capacities $\delta_{u,bi}/\delta_{u,uni}$
Tatsuya [8]	M35X: $\delta_{u,uni}$=2.00%	W35H: $\delta_{u,bi}$=1.50%	0.75
Kabeyasawa et al. [9]	WA1D: $\delta_{u,uni}$=3.73%	WA2D: $\delta_{u,bi}$=2.80%	0.75
	WB1D: $\delta_{u,uni}$=3.45%	WB2D: $\delta_{u,bi}$=2.91%	0.84
	WC1D: $\delta_{u,uni}$=1.81%	WC2D: $\delta_{u,bi}$=1.52%	0.84
	WD1D: $\delta_{u,uni}$=1.99%	WD2D: ($\delta_{u,bi}$=1.26%)[1)]	(0.63)
Almeida et al. [10]	TW1: $\delta_{u,uni}$=1.00%	TW4: $\delta_{u,bi}$=0.75%	0.75
Mean value			0.79

1) The loading history of WD1D comprises some inconsistencies (cycles with too large amplitudes and subsequent unloading), rendering it impossible to determine a displacement capacity that is consistent in its definition with that of WD1D.

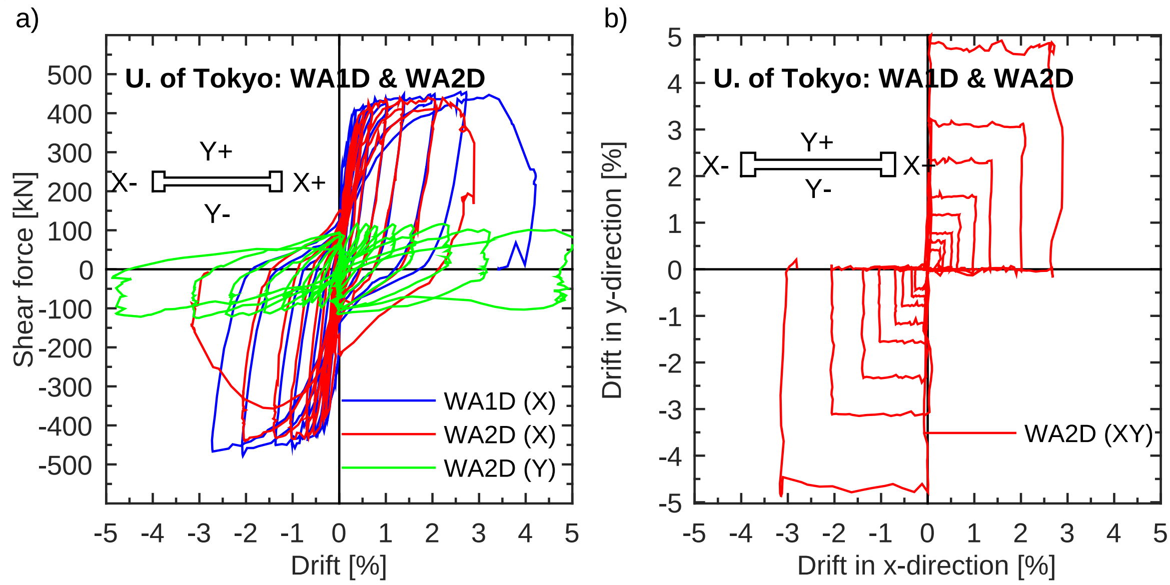

Fig. 1 – Uni-and bi-directional tests on nearly rectangular wall sections of tests from the University of Tokyo (a-b, [9].

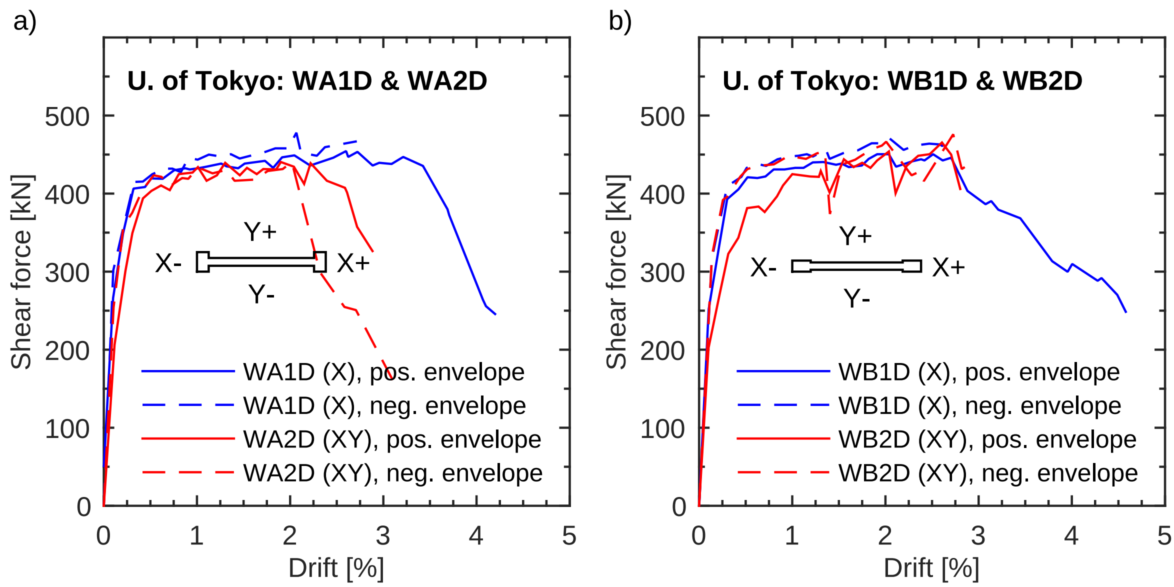

Fig. 2 – Comparison of force-displacement envelopes of uni- and bi-directional tests on rectangular or nearly rectangular wall sections of tests from the University of Tokyo [9].

3 Effect of Bi-directional Loading on Non-planar walls

Non-planar walls are defined here as walls that are designed to carry shear forces in both horizontal (principal) directions. For this discussion, we focus on three quasi-static test programs of non-planar walls with C- or U-shaped sections that include three uni-directional and seven bi-directional tests. The tests were conducted in Ispra by Ile and Reynouard [12], the tests from the University of Washington [13] and the tests at ETH [14] and EPFL [15] in Switzerland.

Two out of the three identical U-shaped walls that were tested at Ispra [12] were subjected to uni-directional loading along the two principal axes while the third wall was subjected to a clover leaf pattern (Fig. 3). For the uni-directional tests (Tests 1 and 2), the force and displacement in the direction of loading are shown. For the bi-directional test (Test 3), response in the y-direction (Fig. 3a) and response in the x-direction (Fig. 3b) are plotted and compared with the corresponding response for the uni-directional test. Results presented in Fig. 2 indicate that the stiffness values and peak strengths for the bi-directional test are similar to those measured in the uni-directional tests for two out of the four loading directions (the positive y- and the negative x-direction). However, for the negative y- and the positive x-direction, the stiffness values and peak strengths are significantly lower for the bi-directional test. The difference in behavior appears to be a consequence of the loading sequence: The peak displacements in the directions positive y- and negative x-direction were reached first when the orthogonal displacement was zero (O→D, O→A). The peaks in the negative y- and positive x-direction were reached when the displacement in the orthogonal direction was non-zero (O→D→F, O→A→E). The observation that a preexisting displacement in an orthogonal direction reduces the maximum attainable strength is consistent with results reported for tests TUA and TUB [14], which were subjected to cycles in the two principal directions before subjected to a cycle in the diagonal direction.

In all three U-shaped walls that were tested at Ispra, longitudinal bar buckling and rupture were observed; however, for Wall 3, more severe concrete spalling and crushing in compression was observed for the bi-directional test relative to the uni-directional tests. Shear compression failure of the compression flange was observed under diagonal loading during the 2% drift cycle for Wall 3, whereas the two walls subjected to uni-directional loading failed during cycles with 3% amplitude (Fig 2; Table 2). If one considers the displacement capacity in the principal directions, the displacement capacity for bi-directional loading was only 67% of that for uni-directional loading (2%/3%=0.67); however, if displacement capacity along the diagonal direction, the reduction in drift capacity is only 6% (2.82%/3.0%=0.94). The comparison of results highlights the importance of the properly (or reasonably) assessing the displacement (or deformation) demands of non-planar walls.

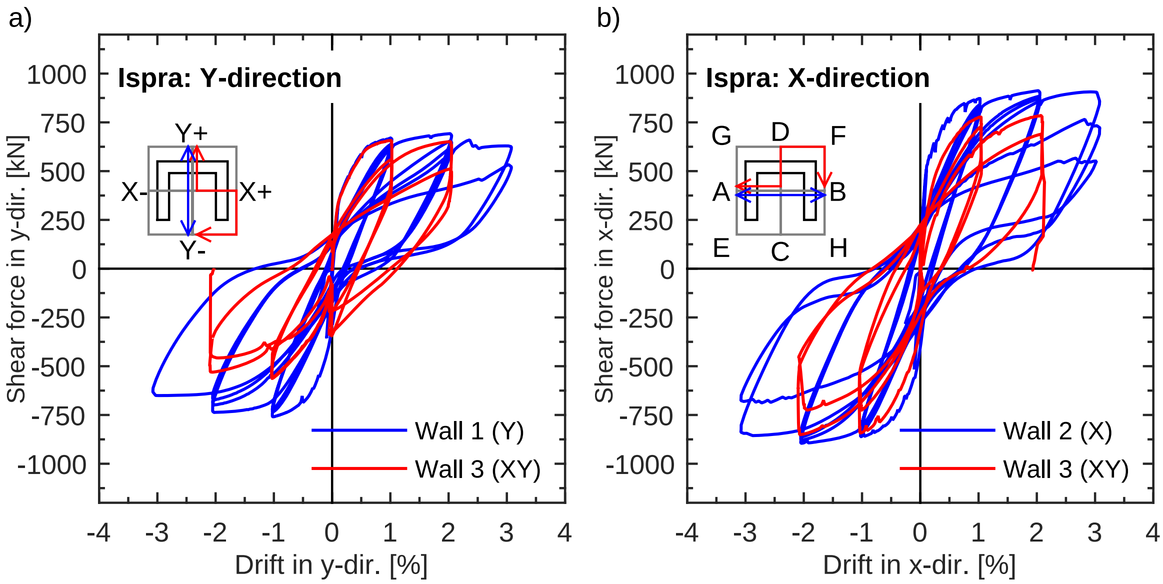

Fig. 3 – Ispra tests on U-shaped walls [12]: Comparison of force-displacement hysteresis for uni-directional loading against force-displacement hysteresis from bi-directional loading (clover leaf pattern): a) Parallel to flanges, b) Parallel to web.

The University of Washington study [13] comprised tests on three identical U-shaped walls of which two (Wall 6 and Wall7) differed only with regard to the loading history. These results are not discussed here in detail but Table 2 compares for the Ispra and University of Washington tests the drift capacities obtained for uni-directional loading to those obtained for bi-directional loading. It shows that bi-directional loading reduces the drift capacities in the principal directions x and y by 10-33%. However, if a resultant displacement is calculated for the drift in x- and y-direction ($\delta_{u,SRSS}$), the drift capacity under bi-directional loading is equal or even greater than the drift capacity for the uni-directional test. In this case, the result is clearly impacted by the geometry of the wall cross-section.

Table 2 – Drift capacities of identical U-shaped walls under uni- and bi-directional loading.

	Uni-dir. tests, Parallel to web	Uni-dir. tests, Parallel to flange	Bi-directional test
Ispra	X: δ_u=3.1%	Y: δ_u=3.1%	X: δ_u=2.1% Y: δ_u=2.1% SRSS: δ_u=3.0%
University of Washington	X: δ_u=2.2%	-	X: δ_u=1.5% Y: δ_u=2.0% SRSS: δ_u=2.5%

4 Summary and research needs

Our understanding of the seismic response of RC walls is largely based on findings from quasi-static cyclic tests, which allow to study the damage evolution in a systematic way. However, the large majority of these tests have been conducted as uni-directional tests and it is therefore important to understand in which aspects results from uni-directional tests differ from those of bi-directional tests. This paper is the result of an ongoing effort of a working group of the NSF SAVI Wall Institute to assess the state-of-the-art of the effect of bi-directional loading on wall performance and to outline future research needs.

Tests on planar and non-planar walls showed that the stiffness is not significantly affected by bi-directional loading. For planar walls the strength is also rather independent of the load path while for non-planar walls the load path has an effect on the strength that is attained in the two principal directions. The in-plane deformation capacity of planar walls subjected to bi-directional loading is approximately 20% smaller than that of walls subjected to uni-directional loading. For non-planar walls similar reductions were observed. However, the displacement capacity in the diagonal direction under bi-directional loading is similar than the displacement capacity in the principal direction under uni-directional loading. These results are based on observations from five pairs of planar walls and two pairs of non-planar walls. The tests differed largely in terms of geometry, axial load ratios, setups, failure modes and bi-directional load paths. It is therefore difficult to derive general rules from this reduced data set and further experimental as well as numerical research on the effect of bi-directional loading on RC wall response is needed. The following sections outline a selection of open research questions that the authors consider relevant. These relate to load path effects, out-of-plane stability of walls subjected to bi-directional loading, system effects and the design of non-planar walls for bi-directional action.

4.1 Load path effects

While for uni-directional tests, the loading protocols differ typically only with regard to the number of cycles per drift level and the drift interval, the differences between bi-directional loading protocols are much greater and they differ in terms of shape, number of directions considered in one protocol, loading sequence, etc. Most commonly used load paths follow criss-cross, clover leaf and sweep patterns. Based on the previous findings, the following points should be investigated i) the effect of axial load ratio and failure mode on the sensitivity of the wall response to load path effects, ii) the effect of the load path on shear lag of non-planar walls, iii) the behaviour of walls that carry shear forces close to the ACI design limit and iv) the effect of actual load path that a wall is subjected to during an earthquake.

4.2 Out-of-plane stability of walls subjected to bi-directional loading

Failure of walls involving significant out-of-plane deformations was observed after the earthquakes in Chile and Christchurch [4], [5], [18]. Often flanges of core walls was a concern [5]. Current models for assessing the out-of-plane instability of reinforced concrete walls (e.g., [19], [20]) do not account for a strain gradient across the wall thickness and corresponding out-of-plane shear forces. Neither do they account for out-of-plane displacements at the wall top, which result from deformations of walls in the orthogonal plane. Furthermore, the boundary conditions provided by the adjacent wall sections are rather complex and the proxy of a pinned-pinned beam for the boundary element, which underlies the models in [19] and [20], might not be very suitable. Further open issues concern the interaction of the out-of-plane deformations with other failure mechanisms such as crushing of concrete and local buckling of longitudinal bars. Wallace et al. [5] found, for example, that spalling and crushing of the concrete rather than yielding of the longitudinal reinforcement might be the triggering mechanism for out-of-plane instability of RC walls [19], [20]. These questions require further experimental and analytical investigations. These open issues should also be extended to walls with a single layer of longitudinal reinforcement, which are particularly susceptible to out-of-plane instability [11].

4.3 System effects

Quasi-static cyclic tests are typically performed using isolated structural walls. In reality, however, walls are part of structural systems that comprise also slabs, gravity columns and often coupling beams. Due to shear forces and moments transmitted by slabs and beams and axial restraints provided by columns, the force demand on a wall as part of a structural system might differ considerably from that of a wall tested in a quasi-static cyclic test where axial load and shear span are typically kept constant throughout the test. In particular the importance of the role of slabs was highlighted by shaking table tests on RC wall buildings or slices of RC wall buildings [21]–[23]. Open questions relate to (i) the influence of slabs on the torsional stiffness of core walls (i.e. sections with U-shaped or even more complex sections) and the interaction of torsional and flexural stiffness, (ii) the influence of openings in slabs on the load transfer from slab to wall, (iii) the validation of different numerical modelling approaches for walls and wall-slab interaction, and (iv) drift capacity of wall-slab connections.

4.4 Designing for bi-directional action

Current design codes do not provide design recommendations that are specific to non-planar walls. Since most wall tests have been carried out on planar walls, design guidelines in codes were derived for this type of walls. Some codes provide general guidelines for non-planar walls such as that the sections should be taken as integral units and the walls be designed for the critical loading direction without identifying, however, how this critical direction should be determined. Open questions relate in particular to the confinement of the flange ends, the out-of-plane stability of flange ends, and the shear force capacity of flanges. With regard to the latter, experimental results have shown that for U-shaped walls subjected to diagonal loading, the majority of the shear force is carried by the flange in compression [12], [14], [15]. Reynouard and Fardis [24] suggest assigning the entire shear force in y-direction to a single flange. This might however lead to very large shear demands in particular if sections with more than two flanges are considered (e.g. E-shaped sections).

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