Behavior of Thin Shear Concrete Walls During Earthquakes in Last Decade

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Abstract: **Many researchers have reported numerous thin shear concrete walls failures. The aim of this study is to present the performance of thin shear concrete walls during past earthquakes of last decade. There are four aspects with the help of which behavior is being evaluated; (i) flaw identification in thin shear concrete walls, (ii) governing mechanical property in dominant flaw, (iii) alternate approach to improve governing properties, and (iv) additives in concrete. Various researchers explored different non-conventional materials to change the post cracking behavior of concrete. The output of using non-conventional materials to enhance mechanical properties of concrete are reported. There is a need to explore behavior of thin shear walls with non-conventional materials.**

Keywords**: Earthquake, flaws, non-conventional materials, thin shear concrete wall.**

I. INTRODUCTIN

Shear walls are used in earthquake prone region as a lateral force resisting system and a path to carry vertical load to the base. Chile, New Zealand, Canada and Colombia have adopted these type of shear wall in their buildings [1]. Literature review tells that during the last decade, two major earthquakes in Chile and Christchurch, New Zealand left a number of buildings damaged due to thin shear wall failure. In 2010 Chile earthquake, more than 100 buildings were damaged due to shear wall failure [2]. In Santiago, number of mid and high-rise buildings shear wall experienced failure in lower stories [3]. Most buildings damaged were medium rise buildings having thin unconfined concrete walls with high axial stresses [1]. Building having concrete shear walls showed effective seismic performance during 1985 Chile earthquake [4]. During 2010 earthquake in Maule, Chile and 2011 earthquake in Christchurch, New Zealand these walls did not give the expected ductile behavior. Buckling of longitudinal rebars and spalling of concrete was observed [1].

The mode of failure for concrete shear walls is flexure. When the thickness of the walls is reduced, the least governing parameter i.e. is compression starts to govern. Crushing of concrete happens abruptly with little or no prior warning. Compressive failure was observed in 2010 Chile earthquake in mid and high-rise buildings. Junemann et al. [1] highlighted that the failure was due to crushing and spalling of the concrete cover, thus generating a horizontal crack that initiates at the free end of the wall and stretches to entire length. Number of thin shear without confined reinforcement failed in compression during 2010 Chile earthquake. Walls not having proper confinement are susceptible to buckling of longitudinal reinforcement and crushing of concrete.

Limiting the compressive strain, increase in minimum thickness of wall and proper confinement of boundary element can avoid brittle failure of thin walls. There is a need to promote cheap and locally available materials in order to save cost without compromising on mechanical properties. Non-conventional materials like natural fibres have a potential to increase mechanical properties of concrete and improve the post cracking behavior of concrete. Compression failure being the dominant flaw in thin shear walls, natural fibres which increase toughness index can change the mode of failure from brittle to ductile. Natural fibers are durable (i.e. there is no significant decrease in strength with increase in life of structure). Natural fibres have good dynamic properties i.e. they can absorb a certain amount of force being applied to the structure. This will be effective in case of thin shear concrete wall as a certain amount of force will be absorbed by the fibre. Increasing cost of steel rebars and corrosion issues have promoted the use of corrosion resistant rebars like GFRP. Corrosion of steel affects its mechanical properties especially ultimate stress and strain. This prompted to look for alternate material to replace steel rebars in future construction. GFRP rebars have gained attention due to its high chemical resistance, low cost, high corrosion resistance and high strength to weight ratio [5]. Fibre reinforced concrete (FRC) will create a bridging effect with unstable concrete and glass fibre reinforced polymer (GFRP) rebars will act as corrosion resistant tensile reinforcement.

II. FLAW IDENTIFICATION IN THIN SHEAR CONCRETE WALLS

More than 70% of population was affected during 2010 Chile earthquake. Thin shear walls were constructed to support floor slabs and also control lateral forces i.e. wind and earthquakes. Latin American countries build thin walls with single reinforcement mesh in buildings. A common failure mode for these thin walls is out of plane failure [6]. Large unsupported length of web near the critical portion at base of wall are prone to out of plane buckling under cyclic loading [7]. In Chile, it's a common practice to make the partition wall between rooms a shear wall in high-rise buildings. Walls having a thickness of 200 mm or less can be considered as thin shear concrete walls [8]. Most of these thin shear walls were of thickness 120 mm to 200mm. When the length of shear wall decreases while going down the structure, there is a sudden increase in demand of compressive strain. This in turn leads to crushing of concrete leading to a catastrophic failure [8]. More than 100 buildings were damaged in 2010 Chile earthquake which had a magnitude of 8.8 on richter scale [2]. Old frame structures are very rare in western Canada. Majority of pre 1980s buildings have shear walls for resisting lateral loads (i.e. earthquake and wind loadings). Shear walls are expected to perform better than the frame structure but at the same time they are susceptible to brittle failure mode. In 2010 Chile earthquake and 2011 Christchurch earthquake, buildings having shear wall faced severe damage due to structural configurations and brittle mode of failure of thin shear walls [9]. Crushing and spalling of concrete along with buckling of longitudinal reinforcement was observed over the length of the wall in 2010 Chile earthquake [10].

Chilean Seismic code 1996 did not restrict any structural irregularities thus number of buildings were built with horizontal irregularities. A 15 story Alto Rio Condominium building in Concepcion shown in figure 1 (a) prior to earthquake and figure 1 (b) shows the collapsed building after the earthquake. This building was designed in 2008 and had shear walls which had an offset at the first story towards which it collapsed as shown in figure 1 (c). Figure 1 (d) shows the plan at ground floor of the building having setback. This vertical irregularity resulted in an increase of compressive stress which led to crushing of unconfined concrete at first story level. These shear walls were slender walls without confinement reinforcement at boundaries of the wall. It was observed that crushing of concrete along with tensile failure of reinforcement within wall triggered total collapse of building [3].

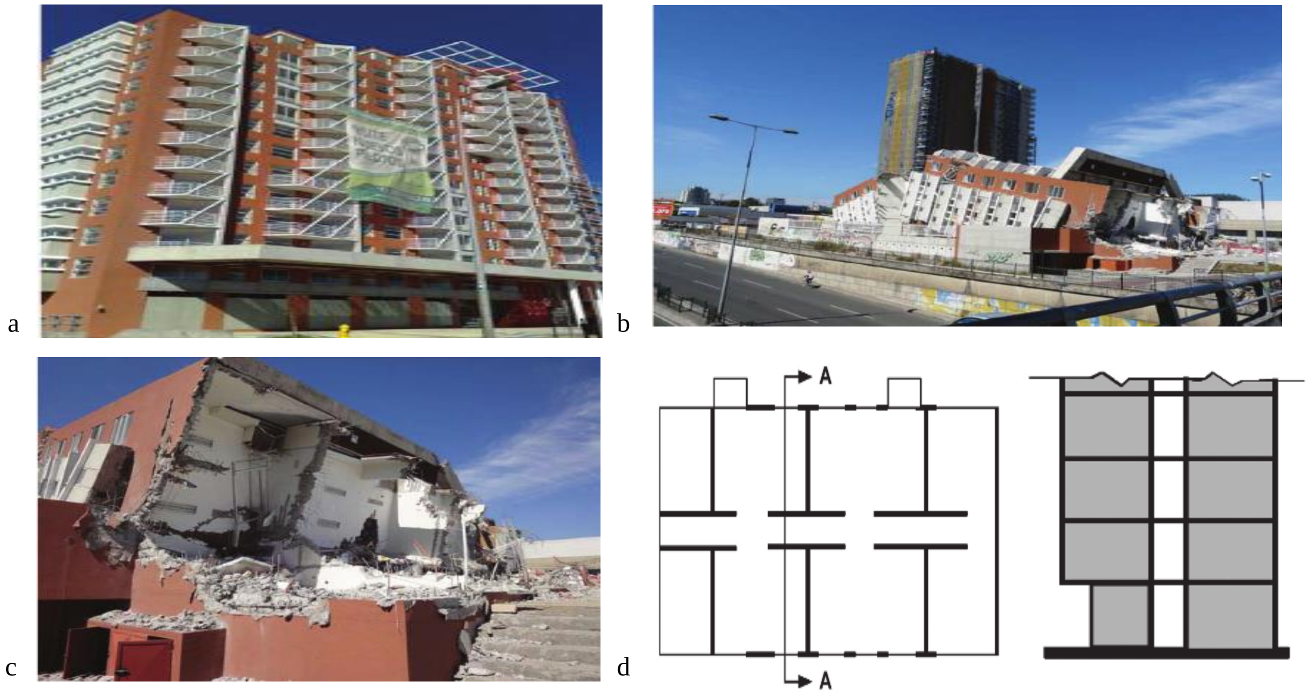

Figure 1: Alto Rio Condominium building in Concepcion; (a) building prior to earthquake, (b) building post-earthquake, (c) failure of shear wall, and (d) approximate plan of building [3]

III. Governing Mechanical Property in Dominant Flaw

A common type of failure observed in high rise buildings was compression failure of thin shear walls as shown in figure 2. Figure 2 (a) shows buckling of reinforcement due to opening of cross ties subsequently leading to spalling of concrete. Lack of boundary elements and rebar buckling is evident in figure 2 (b). Pyne Gould Building in Christchurch, New Zealand collapsed as east core wall failed abruptly in compression. The wall had single mesh of reinforcement and had a thickness of about 200 mm. It was observed that most of thin shear walls in Chile did not have confinement reinforcement. Transverse reinforcement had a 90 degree hook around the two longitudinal rebars at the end of the shear wall [8]. Sattcioglu et al. [3] highlighted that number of mid and high rise buildings in Santiago faced shear wall failure in lower stories due to compression failure of slender thin shear walls.

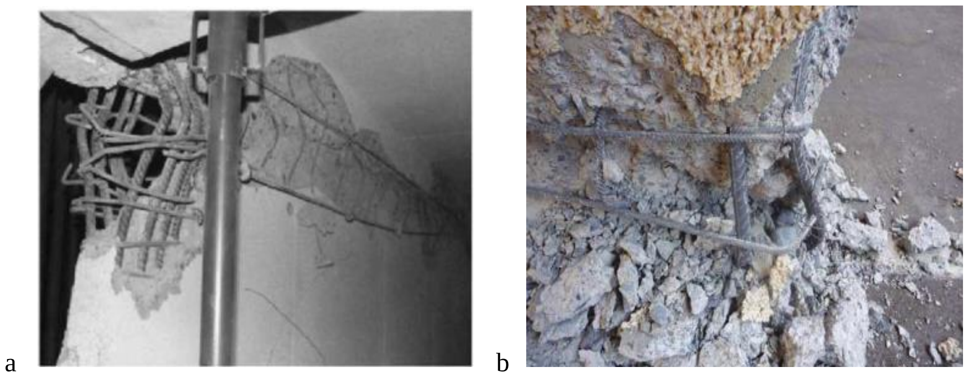

Figure 2: Failure of shear wall, (a) flexural compression failure, and (b) buckling of vertical bar due to lack of boundary elements [8]

During the 2010 earthquake in Chile, compressive failure in thin shear wall was observed in several high rise buildings. Experiments conducted showed that thin shear concrete walls with two layers of transverse reinforcements failed in compression due to low strain as thin concrete layer between the horizontal reinforcement became unstable [2]. Observation of buildings showed that the compression in walls can trigger crushing of concrete along with buckling of longitudinal reinforcement at ground level of wall in tall buildings. Reinforcement buckling and tension could result in breaking and pullout of longitudinal of rebars due to tension in case of inadequate development lengths [11]. The building code of Chile (NCh 433.96) allowed the construction of slender shear walls in multistory buildings. A small wall thickness of 150 mm was permitted with ties to prevent buckling of reinforcement. There was no requirement for boundary zones in these thin walls. This resulted in shear walls were damage as there was crushing of concrete and buckling of longitudinal reinforcement throughout the length of wall [3].

An experimental investigation was carried out by Adebar [8] in which multiple wall samples were subjected to axial compression. The parameters considered were thickness of wall, transverse reinforcement (i.e. no horizontal rebars, single and double layer), clear cover of transverse reinforcement and height. It was observed that walls without any ties failed at a strain of 0.001. The crushing of concrete occurs without any warning (i.e. without prior warning). Thinner walls with single reinforcement mesh failed in a brittle way but at a higher compressive strain as compared to walls having double reinforcement mesh. It was due to large volume of undamaged concrete in walls with single layer of reinforcement. The observations from nonlinear finite element modeling for a wall step-back irregularity showed an increase in demand of compressive strain at the compression edge of short length concrete wall supporting the overhanging concrete shear wall above. Adebar and Lorzadeh [12] reported that a twenty-two story Grand Chancellor hotel faced severe damage due compression failure of concrete wall in lobby. The wall supported a cantilever transfer girder at sixth floor. Segura and Wallace [13] tested two thin wall specimens under combined axial loading and increasing cyclic shear and moment. The wall specimens represented lower part of a cantilever wall of eight story building. The varying parameters in specimens were depth of compression zone and arrangement of vertical and horizontal rebars. The results showed a brittle compressive failure as the thin compressive zone was not able to distribute compressive strain over a considerable length leading to crushing of concrete. Arteta et al. [14] conducted an experimental investigation by casting seven boundary elements of concrete shear walls subjected to compression. The horizontal reinforcement for specimens was such that either it matched or exceeded the code requirement. A brittle axial failure was observed in wall specimens after being subjected to monotonic loading.

IV. Alternate Approach to Improve Governing Properties

To avoid brittle compression failure in walls, increasing the thickness of wall and changes in detailing provisions (i.e. confinement of boundary zones) have been suggested in studies. The experimental investigation showed that wall specimens having ties with 90 degree hooks never opened. Hence, buckling of reinforcement can be avoided which triggers crushing of concrete. It is suggested that there should be a limit on the compressive strain depth to a certain portion of wall which will depend on the drift demand [8]. Shear walls without sufficient boundary confinement fail in a brittle manner in compression zone. As the compressive strain capacity of wall maybe less than what was assumed. In order to avoid brittle mode of failure and buckling of web, the compression stress block of the walls must be limited to ensure a tension controlled failure in concrete walls [15].

Wallace [16] suggested to design the walls for ductile compression yielding by limiting the slenderness and minimum thickness of wall. Changes to the displacement design of shear wall were also recommended for ACI 318-11. Junemann et al. [17] suggested to increase the wall thickness or reduce the wall stresses to improve in plane bending and compression of wall as confining the boundary does not have a great amount of impact on ductility of wall. The Chilean code does not limit the use of structural irregularities (i.e. setbacks and discontinuous shear walls) which in turn increases the deformation demand leading to global failures [3]. A limit on these irregularities can limit the failure of thin shear concrete walls. Shear walls are protected against shear failure by design capacity approach but at the same time number of flexural compression failure occurred in Christchurch. To avoid such type of failure, modification of shear wall design provisions will help in improving the ductility of walls. Sufficient boundary confinement will change the brittle mode of failure to ductile failure [2].

V. Additives in Concrete

Experimental studies showed that properly confined boundary elements do not show a complete ductile behavior when subjected to pure compression by conforming to ACI 318-11 detailing requirements only [14]. Hence, there is a need to explore non-conventional material to change the brittle mode of failure to ductile mode of failure. Natural fibres are cheap and locally available material with a potential to change the post cracking behavior of concrete without compromising the mechanical properties of concrete. Izquierdo et al. [18] used sisal fibre in hollow concrete blocks, wallette and walls. It was observed that sisal fibre increased the ductility of the blocks as the fibre bridged the opening cracks and prevented further discontinuity of the material. Due to low elastic modulus of sisal fibre, they become effective after cracking of concrete hence, there is an increased energy absorption due to which wallettes can withstand increase in loading even after cracking. Madandoust et al. [19] investigated the effect to rice husk ash on properties of concrete and its durability. The durability was assessed by placing the specimen in extreme environment for 11 months. It was observed that partial replacement of cement by rice husk ash increased the durability of concrete and there was an increase in compressive strength of concrete at later ages. Ali et al. [20]

investigated the mechanical and dynamic properties of concrete. The varying parameters were fibre content (i.e. 1% - 5%) and length of fibre. The testing result showed an increase in damping of coconut fibre reinforced concrete beams while a decrease of fundamental frequency of beam was observed due to damage. Further test results revealed that 5% fibre content and 5 cm length of fibre increases the compressive toughness unto 21% as compared to PC. Islam and Ahmed [21] highlighted the influence of jute fibre on the properties of concrete. The results showed a positive impact on compressive strength of concrete with low percentage of fibre content (i.e. 0.25%). Compressive strength of jute fibre reinforced concrete increases with the increase of curing age. The failure pattern of specimen during compressive testing showed that jute fibre decreases the width of the cracks hence, altering the cracking pattern of concrete. Zakaria et al. [22] concluded from his experimental investigation of jute fibre in concrete that there is an increase in mechanical properties by keeping the fibre content of 0.1% and 0.25% with the fibre length of 10 mm and 15 mm. Malai and Datta [23] conducted an experimental investigation on bamboo reinforced slabs. An enhancement in load carrying capacity and deformation ability was observed by using bamboo strip as reinforcement as compared to plain concrete and reinforced cement concrete (RCC). Lima et al. [24] conducted an experiment to evaluate the durability of bamboo fibre. Specimens were exposed to wetting and drying cycles. Samples with concrete were kept in water and samples without concrete were kept in calcium hydroxide. The results of the tests showed no noticeable change in mechanical properties of bamboo fibre proving the durability of bamboo fibres. Zia and Ali [25] studied the behavior of fibres in concrete to control the rate of cracking in canal lining. It was observed that fibres are effective in controlling the rate of cracking and an increase of compressive energy absorption and compressive toughness index was observed as compared to plain concrete (PC). Mozzali et al. [26] concluded that fibres like macro polypropylene and polyethylene are effective in controlling the width of cracks and a delay in crack initiation. Fibres also have the ability to enhance the dynamic properties of concrete. Table 1 summarizes the dynamic properties of fibres.

Table 1: Dynamic properties of fibre reinforced composites

Reference		Fibre	Conclusion
1.	Ali et al. [20]	Coconut	Increase of fibre content increases the damping ratio and reduces the fundamental frequency especially after cracking of specimen. Fibre length of 5 cm and 5% fibre content has the best dynamic properties.
2.	Hussain and Ali [27]	Jute	Addition of jute fibre in concrete increases the damping ratio and dynamic elastic modulus by 100% and 68%, respectively.
3.	Yan and Chouw [28]	Coir	Fibre decreases the fundamental frequency, dynamic Poisson's ratio and modulus of elasticity but significantly increases the damping ratio. It was observed that jute fibre reinforced composite showed a better dynamic behavior.
4.	Omar et al. [29]	Jute and kenaf	Jute fibre had more compressive modulus, flow stress and compressive strength increased upon dynamic loading compared to kenaf fibre.

John et al. [30] investigated the durability of coconut fibre. The fibres were 12 years old and were taken from internal and external walls of houses. SEM analysis showed that fibres were undamaged even after being exposed to 12 years of natural environmental conditions. Lignin content in fibre was same for internal and external wall. Shivaraj et al. [31] highlighted the durability of coconut fibre. The mechanism of testing was 2 years of wetting and drying cycles of specimens and it was concluded that there was no decrease in mechanical properties of coconut fibre reinforced concrete. Prasannan et al. [32] investigated the compressive, flexural and split tensile strength of banana fibre. Amount of fibre content used was 1% and 1.5%. It was observed that flexural and split tensile strength increased while compressive strength remained same after 28 days of curing. The increase was directly proportional to the amount of fibre. It was observed that banana fibre has small elongation and is light in weight. Banana fibre improves the post cracking behavior of concrete due to its effective bridging property. Farooqi and Ali [33] investigated the compressive behavior of wheat straw reinforced concrete. It was observed that the compressive toughness of natural wheat straw reinforced concrete increased by 14% as compared to plain concrete. There was a bridging effect in case of wheat straw reinforced concrete whereas brittle failure was observed for plain concrete.

Corrosion of steel affects its mechanical properties especially ultimate stress and strain prompting the use of glass fibre reinforced polymer (GFRP) rebars. Reduction in ultimate elongation is also a major issue due to corrosion of steel [34]. Arfa et al. [35] conducted an experimental investigation on GFRP reinforced squat walls. It was observed that GFRP reinforced walls can undergo high deformation if designed and detailed properly without compromising on its strength. Due to the elastic nature of GFRP rebars, cracks were realigned and then closed which helped in proper distribution of shear deformations along the height of squat wall. Smaller diameter and closer spacing of GFRP rebars in column showed more ductility resulting in a gradual failure pattern. Afifi et al. [36] highlighted that an effective confinement and ductility can be achieved by using close spaced GFRP transverse reinforcement with a small diameter as compared to large diameter with more spacing. Mohamed et al. [37] conducted an experimental study on GFRP reinforced shear wall under lateral cyclic loading. The results showed that if GFRP reinforced shear walls are properly designed, they can reach their flexural capacities with no decrease in strength. Based on limited test results Deitz et al. [38] concluded that compressive Young's modulus of GFRP rebar is approximately equal to Young's modulus in tension. Chaallal and Benmokrane [39] concluded from limited fatigue tests on GFRP that fatigue performance is satisfactory for GFRP reinforcement. The mechanical characteristic described indicate that an engineer can design structural elements like column and bridges with GFRP rebars. Zang et al. [40] highlighted that GFRP in shear wall shows same load carrying capacity and deformation ability as compared to same reinforcement ratio of steel in shear wall.

VI. CONCLUSIONS

During 2010 Chile earthquake and 2011 Christchurch, New Zealand earthquake buildings faced severe damages. Thin walls failed in compression leading to crushing of concrete. Studies have suggested to change the design provisions in Chilean code for shear walls. Suggestions are made to increase the minimum thickness of wall, limit the vertical irregularities in walls and reduce the axial compression load on shear walls. Arteta et al [12] highlighted that even enhanced detailing of concrete wall did not show the expected ductile behavior. There is a need to increase the compressive toughness of concrete. Non-conventional materials like natural fibres have the tendency to increase the compressive toughness of concrete. Natural fibres have the tendency to enhance the post cracking behavior of concrete by bridging phenomena. They change the brittle mode of failure into ductile without compromising on mechanical properties. Use of GFRP rebar is a step towards corrosion free reinforcement without compromising on the deformation and load carrying capacity as compared to steel.

VII. RECOMMENDATIONS

An experimental investigation is required to verify the effectiveness of non-conventional material in thin shear concrete walls. Bond behavior of GFRP rebars with fibre reinforced concrete in shear walls needs to be investigated for its practical implementation.

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