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The Capacity of Shear-walls Made with Caribbean Timber Species

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Abstract: *Timber has traditionally been used to construct buildings in the Caribbean, and is still utilised fairly extensively in low-rise residential buildings. These timber buildings are generally non-engineered structures and perform poorly when subjected to hurricane forces. Improved hurricane performance could be achieved by understanding the complex load transfer mechanisms in buildings subjected to wind loads. The lateral force-resisting system comprises the diaphragms (roof and floors) and shear-walls. The shear-walls are the primary structural sub-component responsible for providing lateral load-resistance capacity in timber buildings. Robust design of these elements is predicated on the availability of reliable shear-wall capacity data and engineering design properties for the relevant timber species. However, design data are not available for Caribbean timber species. Experimental research was conducted on nailed, plywood-sheathed shear-walls with Caribbean Pitch Pine framing to produce shear capacity data, which in-turn can inform the design of hurricane-resistant buildings using these Caribbean timber species in accordance with the National Design Specification for Wood Construction (NDS-2005) and the Special Design Provisions for Wind and Seismic Design (SPDWS-2005) codes. A total of ten shear-walls were tested in accordance with the American Standard for Testing Materials, ASTM E-564 procedures. The results obtained from this testing programme were compared with results from the SPDWS-2005 for wood-frame plywood shear-walls of similar construction.*

Keywords: *Timber, Buildings, Shear-walls, Racking, Hurricane forces, Lateral loads*

1. Introduction

Timber has been traditionally used to construct buildings in the Caribbean, and is still utilised fairly extensively in low-rise residential buildings. However, the vulnerability of these buildings to damage by hurricanes have been exposed over the years: Hurricane Ivan in 2004 caused mass destruction to the housing stock in Grenada; and Hurricane Tomas in 2010 caused damage to 93% of the buildings in St. Lucia (Prevatt et al., 2010). The poor hurricane performance of timber buildings in the Caribbean results from a lack of engineering design; poor construction techniques; and the absence of building codes with reliable design specifications for Caribbean timber species.

Hurricane-resistant design requires an understanding of the complex load transfer mechanisms in buildings subjected to wind loads. The lateral force-resisting system comprises the diaphragms (roof and floors), which can be rigid or flexible, and the shear-walls. The lateral forces induced by wind are transferred to the diaphragms and then transmitted through inter-element connections to the shear-walls, which then transfer the resulting shear and uplift forces to the building foundations by anchorage. Thus, the shear-walls are the primary structural sub-component responsible for providing hurricane resistance in timber buildings. Effective design of these elements is based on the availability of reliable shear-wall capacity data and engineering design properties of the constituent materials.

Timber buildings in the Caribbean are predominantly constructed with local species of solid timber and wood panels (i.e. plywood). Some North America species (e.g. Southern Pine) and plywood from Brazil are used. Currently, timber designs in the Caribbean region are based on North American codes, namely the National Design Specification for Wood Construction (AFPA/AWC, 2006a) and the 2006 International Building Code (ICC, 2006). The relevant companion code to the NDS-2005 for shear-wall design is the Special Design Provisions for Wind and Seismic Design (AFPA/AWC, 2006b) which include provisions and design data for the shear capacities of wall panels with North American species. However, these codes do not include engineering design properties for Caribbean timber species. There is a paucity of design data on local species to facilitate engineering design.

This paper investigated the capacity of shear-walls framed with Caribbean Pitch Pine (*Pinus Caribbea*) species, with a view to developing the relevant engineering design data for the improved hurricane-resistance of wooden residential buildings. The data set specifies the nominal shear capacities for designs in accordance with the SPDWS-2005 code (AFPA/AWC, 2006b).

2. Previous Research

A high percentage of the housing inventory of Australia and the south-eastern United States are light frame timber constructions. These regions are prone to hurricane activity. Residential buildings in these countries exhibit enhanced performance to hurricane forces through engineering design based on reliable engineering design data available in relevant building codes (Emerson, 2002).

Research on timber shear-walls has been ongoing for over sixty years with much of the work being conducted in North America and Asia where timber is utilised extensively in low-rise residential buildings. The resistance of timber shear-walls to wind and seismic forces is determined by conducting racking tests on wall specimens. However, shear capacities are influenced by several variables such as wall panel size, construction details, wood species, sheathing material, openings and methods of testing (Hansen, 1985).

Various researchers over the last forty (40) years or so, namely Tuomi and McCutcheon (1978), Itani et al. (1982), Patton-Mallory and Wolfe (1985), Cheung et al. (1988), Dolan and Madsen (1992), conducted experimental investigations of the various parameters that affect the racking capacity of timber shear-walls. Some of the parameters investigated include shear strength, stiffness, sheathing types, framing material, length and opening effects. These were also reviewed extensively by Van de Lindt (2004).

Subsequently, for universal comparisons, tests for determining the shear capacity utilise a basic panel size of dimensions 2,400 x 2,400 mm subjected to incremental lateral loading at the top of the panel to develop the shear capacities (unit shear) for various sheathing types, stud timber species and connection arrangement. Standard procedures for racking tests are prescribed in the American Society for Testing and Materials, ASTM E-564 standard. This standard has gained universal acceptance for experimental research on timber shear-walls and was adopted in tests conducted by the American Plywood Association which formed the basis for the design values for the shear capacity contained in the SDPWS (AFPA/AWC, 2006b).

More recent studies have been conducted to investigate shear-wall behaviour for non-standard configurations and to develop design data for different types of construction, sheathing and wood species. Kermani and Hairstans (2006) studied the racking behaviour of shear-walls sheathed with structural insulated panels (SIPS) as well as walls with openings. Racking resistance of panel-sheathed shear-walls with openings was also investigated by Yasumura (2010). Li and Lam (2009) examined the performance of diagonal-braced shear-walls sheathed both with and without gypsum sheathing and reported significant increases in strength and stiffness. Emerson (2002) tested shear-walls with the framing joints connected with metal plate connections which contributed to enhanced lateral load resistance through moment-resisting-joints. Caprolu et al. (2012) conducted tests to study the anchorage and the splitting failure of the bottom rail in shear-walls due to uplift under the lateral load. Experimental investigations on the behaviour of the connections in wooden shear-walls were also conducted by Du et al. (2012) and Liu et al. (2012).

Moreover, Sartori et al. (2012) and Yan et al. (2012) recently conducted experimental investigations on the mechanical properties of shear-walls. He et al. (2010) investigated the racking capacity of wood shear-walls fabricated using Chinese wood-based panels. Also, Sulistyono et al. (2012) investigated the shear capacity of wall panels with framing from mangium wood. Sartori et al. (2012) investigated the behaviour of timber shear-walls with a combination of lateral and vertical loads and comprised various hold-down anchorage and sheathing panels. Liu et al. (2012) investigated the influence of tests condition and loading protocol in terms of load spreader and hold-downs for fully sheathed walls and walls with openings and Kobayashi et al. (2012) investigated the behaviour of full-scale shear-walls under monotonic and cyclic loading.

3. Shear-wall Tests

An experimental investigation on full-scale plywood sheathed shear-walls was conducted at The University of the West Indies Structures Laboratory. The purpose of the tests was to determine the shear capacity of walls constructed with a local timber specie and to develop the design data for these wall panels. For this study, ten (10) shear-wall specimens of dimensions 2,400 mm x 2,400 mm were tested. A typical wall panel specimen is shown in Figure 1 and comprises Caribbean pitch pine framing and 12 mm thick plywood (Brazilian Pine) vertically oriented and nailed to the frame.

Frame members were all 50mm x 100 mm with studs spaced at 600mm centers, double end studs, double top plate and single bottom plate. Frame joints were formed by end-nailing using 10d common nails to connect the top and bottom plate to the vertical studs. The fastener schedule for the sheathing utilised 8d nails spaced at 150mm on the perimeter and 305mm in the field. Metal tension straps were fabricated and connected to the inner face at the joints between the end studs and base plate using 8d nails and a 16mm anchor bolt.

The shear-wall test setup is shown in Figures 2 and 3. The foundation consisted of a 305 mm x 305mm reinforced concrete beam which was anchored to the concrete test floor using 38mm diameter anchor bolts. The base plate of the wall panel was anchored to the concrete base by means of four 16mm diameter anchor bolts as indicated in Figure 1.

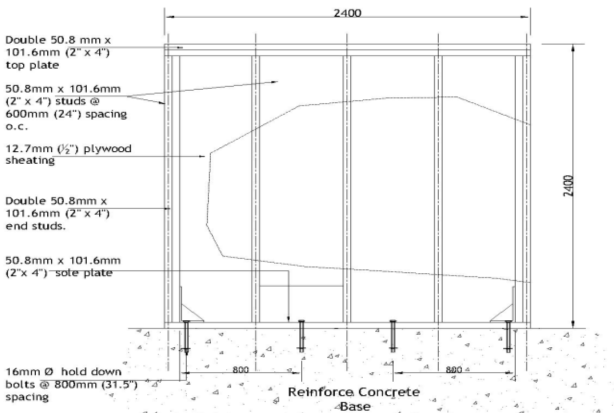

Figure 1. Typical Test Wall Panel

Figure 2. Shear-wall Test Setup

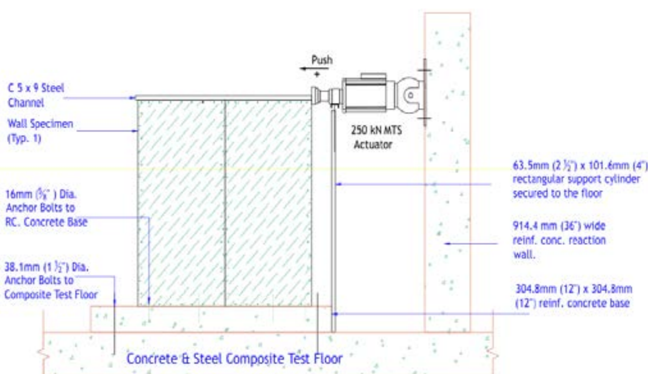

Figure 3. Schematic of Shear-wall Test Setup

A steel channel 127mm wide was attached to the full length of the top of the wall panel using 12mm (1/2”) diameter bolts at 600mm centers to distribute the lateral load as a uniform shear force along the top of the wall. A lateral bracing frame with horizontal rollers attached to the top of the wall panel was installed to prevent out-of-plane deflection while not restraining the racking displacement of the wall specimen during loading.

The lateral load was applied using a computerised testing system comprising an MTS 250 kN hydraulic actuator with integral displacement Linear Variable Differential Transducers (LVDT) attached to the laboratory reaction wall as shown in Figure 2. The system recorded the lateral deflection at the top of the wall panel. Additionally, dial gauges were installed to measure the diagonal distortion of the wall panel and the uplift of the leading stud (at the loaded edge). The shear-wall test was conducted in accordance to ASTM E564. The walls were tested at a constant rate of 0.25mm/sec until failure. Failure was observed when the wall panel racking distortion became excessive with significant structural damage to the sheathing connections and uplift of the studs. The load-displacement results were continuously recorded by the computerised testing system throughout the test and an Excel plot of the load displacement curve was generated.

4. Results

The load-displacement curves for the shear-wall tests are shown in Figure 4. These show that the racking behaviour of the wall panels is nonlinear throughout the test, up to failure. The test standard, ASTM (2006) E564 specifies a minimum of two tests to determine the shear capacity of a particular wall construction and includes the following parameters for defining shear capacity:

Ultimate shear strength, $S_u = \frac{P_u}{b}$ kN / m equation (1)

Global shear stiffness, $G' = \frac{P_{ref}}{\Delta_{ref}}\left(\frac{a}{b}\right)$ kN / mm equation (2)

Internal Shear stiffness, $G'_{int} = \frac{P_{ref}}{\Delta_{int}}\left(\frac{a}{b}\right)$ kN / mm equation (3)

Where,

P_u = ultimate load (kN)
b = length of the wall panel (mm)
a = height of the wall panel (mm)
P_{ref}= 0.33 x P_u
Δ_{ref} = reference displacement corresponding to P_{ref}
Δ_{int} = internal shear displacement
Δ_a = total vertical elongation of the wall anchorage system (at loaded stud)

Table 1. Results of Shear-wall Test

Test	a	b	P_u	P_{ref}	Δ_{ref}	Δ_{int}	Δ_{ult}	S_u	G'	G'_{int}	Δ_a
Panel	(mm)	(mm)	(kN)	kN	(mm)	(mm)	(mm)	(kN/m)	(kN/mm)	(kN/mm)	(mm)
1	2400	2400	26.489	8.7414	13.1	99.98	65.78	10.85	0.67	0.09	35
2	2400	2400	29.31	9.6723	12	71.21	85.6	12.01	0.81	0.14	38
3	2400	2400	23.73	7.8309	10.7	99.98	74.95	9.72	0.73	0.08	30
4	2400	2400	30.74	10.144	13.1	71.21	82.71	12.6	0.77	0.14	38
5	2400	2400	29.145	9.6179	14.2	71.21	82.94	11.94	0.68	0.13	36
6	2400	2400	23.374	7.7134	10	71.21	66.05	9.58	0.77	0.11	38
7	2400	2400	25.949	8.5632	12.1	71.21	89.09	10.63	0.71	0.12	35
8	2400	2400	24.377	8.0444	9.5	85.57	70.38	9.99	0.85	0.09	43
9	2400	2400	26.217	8.6516	11.6	71.21	76.73	10.74	0.74	0.12	41
10	2400	2400	28.327	9.3479	12.5	71.21	80.33	11.61	0.74	0.13	44
Average			26.766					10.967	0.747	0.115	37.8

The results for the ten (10) wall panels tested are given in Table 1. This shows that the ultimate load ranged from 23.37 kN to 30.74 kN with an average of 26.76 kN; and the maximum deflection ranged from 65.78 mm to 89.1 mm. The average global stiffness was 0.75 kN/mm; and average internal stiffness was 0.12 kN/mm; and the average vertical elongation (Δ_a) of the wall panels was 37.8 mm. The unit shear (S_u) represents the shear capacity and ranged from 9.58 kN/m to 12.6 kN/m. Figures 5 and 6 show the variation of unit shear S_u with global stiffness (G') and internal stiffness (G_{int}), respectively, for the wall panels tested. The average unit shear was 10.97 kN/m.

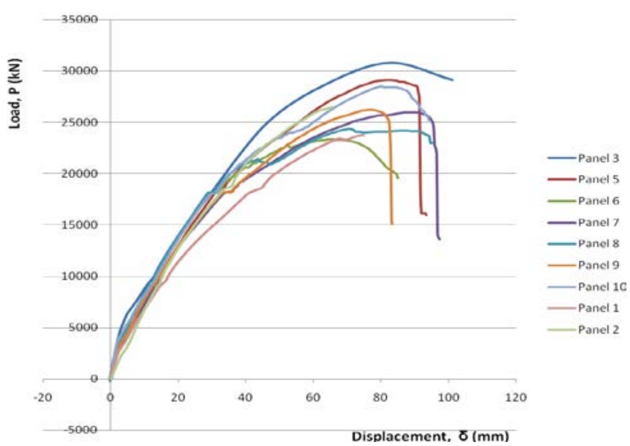

Figure 4. Load-displacement Curves for Wall Panels

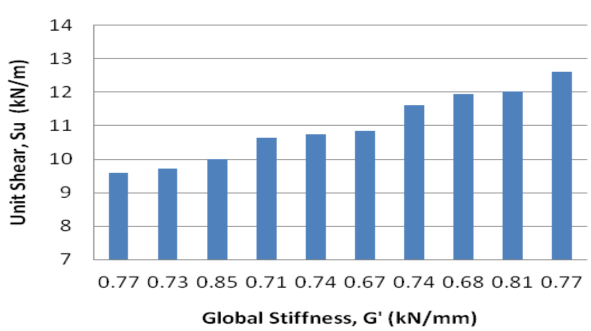

Figure 5. Variation of S_u versus G' for Wall Panels

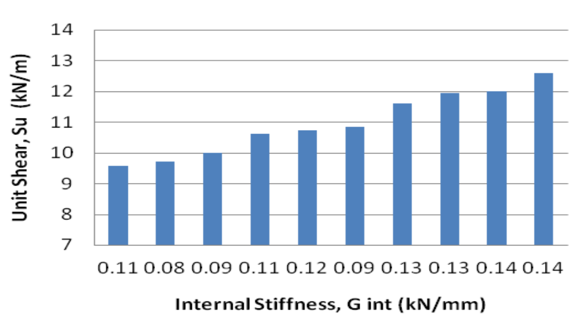

Figure 6. Variation of S_u versus G_{int} for Wall Panels

5. Applicability of the Study

The primary purpose of this investigation was to obtain design values for the shear capacity of walls constructed with Caribbean Pitch Pine timber framing and plywood sheathing. This would inform the design of timber shear-walls using the SDPWS-2005 code (AFPA/AWC, 2006b) and hurricane-resistant buildings in accordance with the NDS-2005 code (AFPA/AWC, 2006a). The SDPWS includes provisions and nominal unit shear capacities for wood-frame Plywood shear-walls constructed with Douglas Fir-Larch and Southern Pine framing based on a specific gravity of 0.5.

For other species the standard recommends that the tabulated nominal shear capacities be multiplied by a Species Adjustment Factor given by C_{sp}= [1 – (0.5 – G)]< 1, where G is the specific gravity of the framing lumber from the NDS. The specific gravity for Caribbean Pitch Pine was obtained from testing as 0.66. Hence, the Adjustment Factor is [1-(0.5-G)] = [1-(0.5-0.66)] = 1.16. Since this exceeds 1.0, a value of $C_{sp} = 1.0$ should be used for Caribbean Pitch Pine framed walls with similar construction for shear-wall design in accordance with the SDPWS-2005 code (AFPA/AWC, 2006b).

For the wall panels tested in this study, the nominal unit shear capacity for shear-walls constructed with Caribbean Pitch Pine framing and plywood sheathing was 10.97 kN/m. These wall panels were constructed with 12mm thick plywood with panel edge fasteners of 8d common nails spaced at 150 mm centres. Applying the Species Adjustment Factor for a similar construction, the nominal shear capacity obtained from the SDPWS-2005 is 10.67 kN/m. Hence, the two values compare favorably as shown in Table 2.

Table 2. Comparison of Nominal Unit Shear Capacities

Wall Type	SDPWS-2005 * kN/m	Present Study ** kN/m	Difference kN/m
Plywood Sheathed Wall - 8d common nails - 6 in panel edge fasteners	10.67	10.97	0.03 (3%)

Notes:
* - Douglas Fir-Larch or Southern Pine Frame
** - Caribbean Pitch Pine Frame

The present study provides data on three (3) critical parameters previously unavailable for designing shear-walls utilising Caribbean Pitch Pine framing and plywood sheathing in accordance with the SDPWS-2005 (AFPA/AWC, 2006b). The shear-wall stiffness G_a (G_{int}), vertical elongation Δ_a, and unit shear v (S_u) are used in the empirical equation given in the code for estimating wall drift. Whereas the unit shear capacity v (S_u) is used in computing shear capacity for shear-walls given in Equations (4) and (5), in accordance with NDS-2005 (AFPA/AWC, 2006a).

$$\nu' = \nu C_{sp} C_{ns} C_{ar} \left[\frac{1}{SF} \text{or } \phi \right] \quad \text{equation (4)}$$

$$V = \nu \left[L_s \right] \quad \text{equation (5)}$$

where,

V = design shear capacity (kN) of a single shear wall segment,

ν = the unfacatored (ultimate) and unadjusted unit shear resistance for the wall construction

ν' = the factored (design) and adjusted unit shear resistance for the total wall construction

L_s = the length of the shear wall segment (total width os sheathing panels in the segment)

C= adjustment factors for timber species (C_{sp}), nail size (C_{ns}) and aspect ratio (C_{ar}) respectively,

SF=safety factor for Allowable Stress Design (ASD)

ϕ =resistance factor adjustment for Load and Resistance Factor Design.

6. Conclusion

This research was conducted to investigate the behaviour of timber shear-walls constructed with plywood sheathing and Caribbean Pitch Pine framing and to develop design capacity data for these structural elements. This is required for designing timber buildings with improved hurricane resistance performance in the Caribbean, since a high percentage of residential buildings in the region are constructed with timber. The shear-walls are the most critical structural element of the lateral force resisting system for timber buildings; however, there is a paucity of design data on Caribbean species.

The load-displacement curves for the wall panels tested indicated nonlinear racking behaviour throughout the test. The average ultimate load obtained was 26.77 kN and the nominal unit shear capacity was 10.97 kN/m. These compared favourably with the value stated in the SDPWS-2005 (AFPA/AWC, 2006b) for timber-framed shear-walls of similar construction with Douglas Fir-Larch and Southern Pine. This indicates that timber structures both in the Caribbean and North America should perform similarly using the native species for the particular region. This also indicates that the majority of failures in the Caribbean would be due to poor engineering designs, since the material properties compare favourably with the North American species.

Caribbean Pitch Pine is the most popular native species utilised in the construction of timber-framed shear-walls in the Caribbean region. Based on this study, design data is now available for the design of plywood-sheathed shear-walls constructed with Caribbean timber species with 8d common nails and 6 inch panel edge fastener spacing. Timber buildings in the Caribbean utilising this form of shear-wall construction could be designed in accordance with the SDPWS-2005 and NDS-2005 codes (AFPA/AWC, 2006a, b).

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