Straw Bale Construction; a Solution for Low Cost Energy Efficient Rural Housing in the Earthquake Affected Regions of Central Southern Chile?

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ABSTRACT: Following the earthquake of February 2010 in central southern Chile almost 80,000 families have been re-housed in "mediaguas," temporary timber emergency shelters 18m2, as they await the rebuilding of their damaged properties. Even before the earthquake, a survey conducted in 2007 by the Chilean charity, Un Techo para Chile recorded 28,578 families living in shanty towns. In addition a study conducted between the winter of 2007 and summer of 2008, showed that a large percentage of the Chilean population live during the winter in poor hygrothermal conditions with over 80% suffering problems with condensation and moulds. An affordable, renewable resource, with excellent insulation properties, currently burned as a waste material adding to carbon emission, straw bales could offer an affordable solution to providing energy efficient housing especially when considering rural locations. This paper presents the research of the authors regarding the hygrothermal performance of straw bales in central Chile, with results from physical test chambers, and the application of this construction typology to designs for permanent housing solutions.

Keywords: Energy, Comfort, Low Cost Housing, Straw Bale, Natural Disaster Relief

1. INTRODUCTION

At 3.34am on the 27th of February 2010 an earthquake of magnitude 8.8 on the Richter scale hit central southern Chile. Affecting an area of around 600km in length and felt by over 80% of the Chilean population, the earthquake left 521 people dead, 56 missing [4], 103,543 dwellings destroyed, 105,039 severely damaged [5] and many more requiring varying degrees of repair.

2. CHILEAN HOUSING SITUATION

Pre-earthquake housing deficit

Even before the earthquake Chile's housing deficit was not insignificant. According to the 2002 census 15% of the urban population were recorded as living in self built shelters or homeless, [6] a figure that rises to 37.64% of the total Chilean population [7] when those sharing dwellings are included. Of this figure the rural homeless population represents 19%.

According to the National Survey of Shantytowns undertaken by the charity 'Un Techo para Chile,' in 2007 there existed in Chile 533 shantytowns (campamentos) housing 28,578 families. Of these 73% were located in the earthquake-affected zone (5-9th and Metropolitan Regions) [2]. Prior to the earthquake 'Un Techo para Chile,' along with other charities and government agencies had the objective of eradicating these slums by 2010 with the provision of definitive housing that met with the Chilean building regulations. Often during this process, as a stepping-stone families would be moved into volunteer built "mediaguas" temporary timber shelters 18m2 costing approximately US$915 [8]

In addition to the quantitative housing deficit Chile also suffers from one that is qualitative. A report on annual household fuel bills of Chilean families indicates that in 2006 all but the richest two fifths of the Chilean population could be classed as energy poor [9,10]. In addition a study by the Chilean national government program for energy efficiency, Programa País Eficiencia Energética PPEE and the German technical Cooperation GTZ showed that a large percentage of the Chilean population live during the winter in poor hygrothermal conditions, with over 80% suffering problems with condensation and moulds [3]. This problem is further exasperated by high usage of freestanding, naked flame, liquid gas or paraffin heaters, or inefficient wood burning stoves.

Although historically adobe was the traditional construction technique in rural central Chile, this has now been replaced by timber and masonry. A survey of the principal building materials of a typical village near Santiago in 2009 recorded 65% of all buildings were of timber framed, timber clad construction; 25% masonry; 7% adobe, principally in the historic centre of the village; and the remaining 3% of timber frame with sheet metal cladding [11]. The majority of the dwellings are without any insulation, apart from those built following the introduction of Chilean Thermal Building Regulations in 2000 for roofs and 2007 for walls. Assuming an average timber cladding thickness of 15mm and an internal finish of 12mm plasterboard this would provide a u-value of 2.362W/m²K, whereas those complying with the Thermal Building Regulations would have a maximum u-value of 1.9W/m²K which although being an improvement is insufficient given the climatic conditions with cold winters and average monthly dry bulb temperatures as shown in Table 1.

Table 1. Maximum (max.), Minimum (min.) and daily average (avg.) dry bulb temperatures ªC for Santiago de Chile. [12]

Month	Max.	Min.	Avg.
JAN	33.0	10.0	21.0
FEB	32.0	9.0	20.3
MAR	33.0	4.0	17.9
APR	30.0	-0.3	14.1
MAY	27.0	-0.3	11.0
JUN	22.3	-1.4	9.1
JUL	20.0	-2.2	7.6
AUG	28.2	-6.0	9.3
SEP	25.3	-0.5	11.4
OCT	29.0	2.0	14.4
NOV	31.0	4.2	17.1
DEC	33.2	8.0	20.2

Post-earthquake housing deficit

Directly following the earthquake the Chilean government, in conjunction with the military and various Chilean and international charities, organised the building of approximately 80,000 [1] “mediaguas”. Of these 4,754 were located in emergency encampments the rest being built on the property of those affected adjacent to their damaged homes. The walls of these timber framed, timber clad, one-roomed temporary structures consist of 5mm thick timber siding with no insulation or internal finishes, providing a u-value of 4.797W/m²K, and considerable infiltrations.

In addition to the 80,000 families housed in mediaguas, many other have taken shelter in the homes of relatives or friends, whilst others continue to inhabit their damaged dwellings. A more complete picture of the increase in housing deficit post-earthquake can be gained from the number of applications for government subsidies for reconstruction. These applications required the presentation of an official certificate, issued by the local government, proving damage or loss of a principal dwelling as a direct consequence of the earthquake. At the closing date for applications, the 27th August 2010 a total of 286,678 applications had been received [1].

Government Reconstruction Proposals

On the 29th March 2010 the Chilean government announced a spending plan of US$2,500 million dedicated to reconstruction [1]. The plan is organised in three main action plans, these being;
(i) Rebuilding, repair and replacement of individual single family dwellings; (ii) Repair and replacement of social housing blocks and neighbourhood masterplans; and (iii) Municipal masterplans. Figure 1 illustrates the area affected by the earthquake and the distribution of these mid to large-scale projects, with 21 projects for social housing blocks, 107 neighbourhood masterplans and 100 municipal masterplans [5].

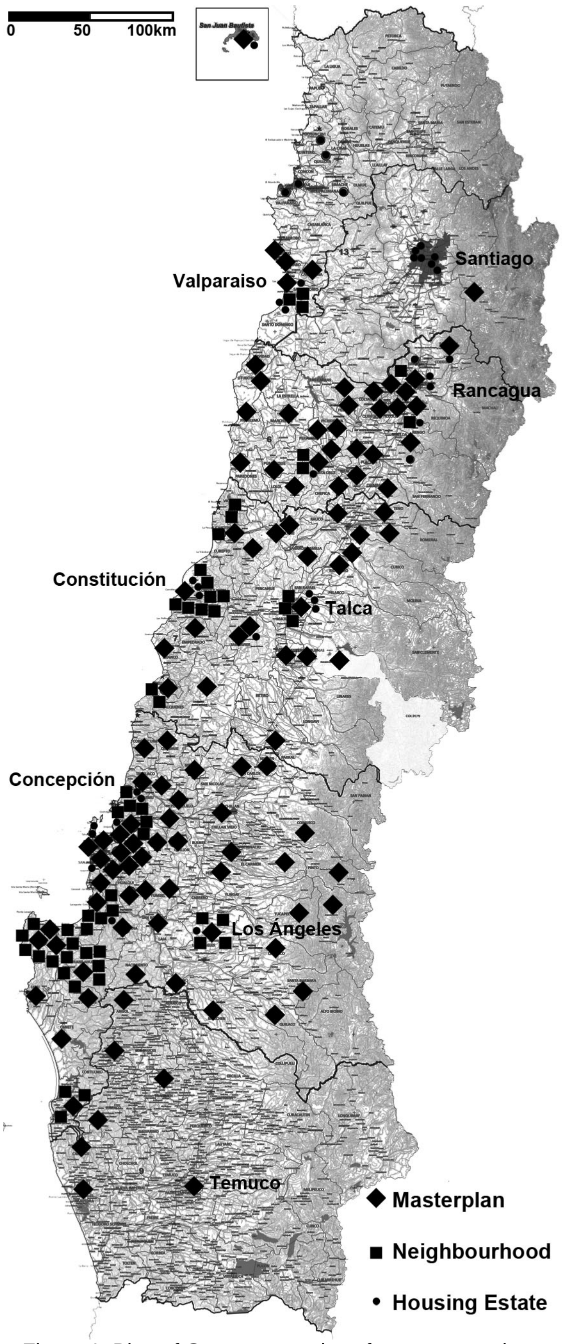


Figure 1: Plan of Government plans for reconstruction at city or town scale (Masterplan) at neighbourhood scale and social housing estates in the 5th-9th Regions [5]

At the scale of the single family dwelling, in an effort to standardise the process and regulate quality, the government has introduced a system of certified housing solutions from which applicants can choose their new-build dwelling. Costing 380UF (approximately US$16,950) these houses have an average floor area of 45m^2 of various construction systems that must comply with Chilean building regulations. To date 41 designs have been certified, the construction solutions of which are as defined in table 2, and a further 115 are under evaluation [1].

Table 2. Materiality of the 41 government approved standard house types presently available for those applying for reconstruction grants. [1]

Structural and insulation solution / Cladding	Timber siding or OSB	Fibre cement	Vinyl siding	Render	Brickwork	Concrete block work	
Timber with ESP or Mineral wool infill	15	7	1			1	24
ESP Insulated sandwich OSB panel	4						4
Uninsulated Brickwork				1	4		5
Cold formed steel with mineral wool		3	3				6
Reinforced concrete with external ESP				2			2
	19	10	4	3	4	1	41

3. COULD STRAW BALES OFFER A SOLUTION?

Turning waste into housing

During the agricultural productive year 2008-2009 Chile planted 281,000 hectares of wheat, 101,000 of oats, 18,500 of barley and 24,000 of rice. [13] This equates to 0.02 hectares per capita of cereal crops. In comparison, the same year in the UK approximately double the amount 0.05 hectares per capita of cereals were planted. [14] Currently in Chile the straw from these cereal crops is viewed as a waste product and is burnt in the fields further adding to carbon emissions and poor air quality. Concerns over the already saturated air pollution in the capital Santiago, lead last year to the prohibition of agricultural fires during the winter months between the 1st of May and the 31st August in the VI Region, the region to the windward side of Santiago. However in 2009 alone 360 prosecutions were brought for infringement of this law.

If the straw was viewed as a resource instead of a waste product the straw from all these crops could be used for straw bale construction, thereby reducing green house gas emissions at source and potentially, emissions arising from the heating of rural dwellings. In addition, the majority of cereal production is concentrated in the central zone of Chile, the zone affected by the earthquake and that where 73% of the families previously living in shanty towns are located. If divided between those families previously homeless and those currently rehoused in mediaguas, the area of straw producing cereal crops per family would equate to 4.2 hectares. Assuming a yield of 2690kg of straw per hectare [15] and an average bale weight of 14.5kg [11] this would equate to 781 bales per family, more than sufficient to build a simple single-family dwelling.

The use of straw or grasses, in construction dates back thousands of years; however the first recorded use of straw bales in construction began in the Sand Hills region of Nebraska in the late 19th century. Faced by a shortage of other suitable building materials the settlers of the area turned to the product of the newly invented mechanical baler. These early constructions used the bales in a load bearing fashion with no additional structural members [11].

Although the most straightforward form of straw bale construction, load bearing or Nebraska-style bale structures present some restrictions and difficulties. These include limitations in opening sizes and maintaining walls and corners plumb. In addition there exist concerns over seismic stability despite Californian tests that have proved good resistance to seismic loading by straw bales encased in steel mesh and cement render [16]. For these reasons some degree of timber structure would appear to be an advantage.

Thermal properties of straw bales

With the combination of the air trapped within the hollow fibres and the overall width of the bale, straw bales provide a high level of thermal insulation. However, being a natural product these values vary considerably depending on compaction, straw type and moisture content. International test results compiled by the authors [11] show coefficients of thermal conductivity (lambda) between 0.034 and 0.15W/mK, and U-values between 0.103, and 0.334W/m^{2}K. These values show a large variation, one that would be perhaps worrying to someone aiming for a zero energy house, however even the worst of these results would provide 5 times the thermal insulation required by law in central Chile.

Test results from physical test chambers

In order to test the thermal performance of straw bale construction under central Chilean climatic conditions, three physical test chambers were constructed at the university's campus Casona de Las Condes in the suburb of Las Condes, Santiago de Chile. These test chambers, each with an equal internal volume, consisted of a timber construction replicating that of a mediagua; a similar timber construction insulated with sufficient expanded polystyrene to comply with the local building regulations (1.9W/m^{2}K), replicating the most common construction solution of the 41 government certified house types; and a third in straw bale construction with a timber frame and 30mm earth render made from recycled adobes. Using Logtag data loggers the internal dry-bulb temperature and relative humidity has been measured hourly since May 2010. It should be noted that during this period the straw bale test chamber had yet to receive its final whitewash finish and as such had a darker surface finish that increases solar thermal radiation absorption.

In addition the three test chambers were simulated using TAS software and recorded external temperatures. An averaged coefficient of thermal conductivity of 0.8 W/mK was used for the straw bale. The results of the simulation, figure 3, can be seen in comparison with the actually recorded dry-bulb temperatures that were recorded on the coldest day recorded to-date the 16th July 2010, figure 4.

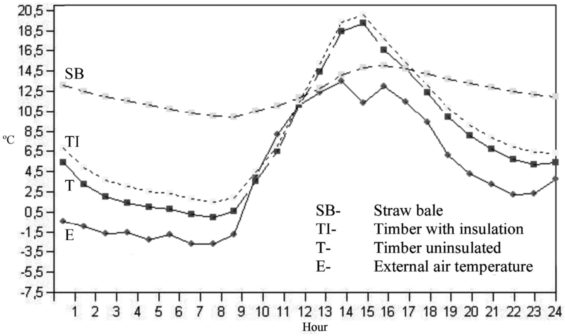


Figure 2: Simulation of dry-bulb temperatures with TAS software 16th July 2010, coldest day recorded to-date.

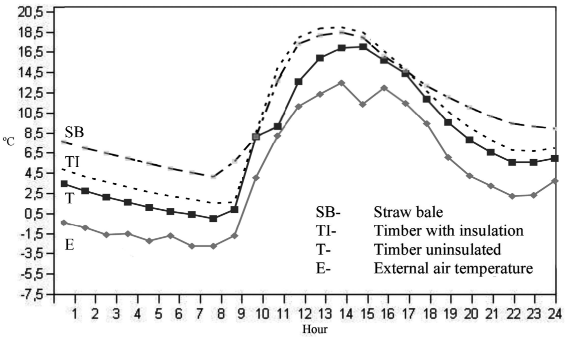


Figure 3: Actual dry-bulb temperatures recorded in physical test chambers 16th July 2010, coldest day recorded to-date.

Whilst the real straw bale construction does not provide dry-bulb temperatures as stable as those simulated it still performs better than the other two constructions.

The dry-bulb temperatures recorded between May and October 2010 demonstrate that as a result of the superior U-values the heating degree hours, are considerably lower for the straw bale test chamber than those for the timber constructions, figure 5. Measurements of relative humidity show that the straw bale construction maintains an internal RH between 25-60% for 82% of the time, in comparison to only 61% of the time for the timber construction and 71% for the insulated timber construction. It is interesting to note that the construction cost for the straw bale physical test chamber was fractionally less than that of the un-insulated timber test chamber, at a cost of US$140 per usable m² as opposed to US$142 [11]. This would suggest that straw bale emergency shelters could financially compete with mediaguas.

Figure 4: Physical test chambers constructed at Casona de las Condes, Universidad Andrés Bello, Santiago de Chile.

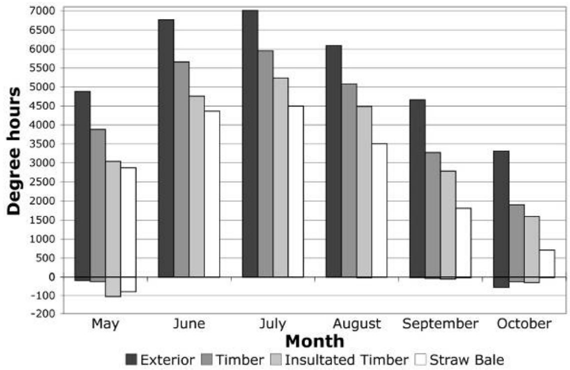


Figure 5: Heating (+) and cooling (-) degree hours calculated from dry-bulb temperature readings in physical test chambers. During winter months May-October 2010

Bureaucratic barriers

The availability of straw bales as a resource and the empirical data gathered so far by the authors would suggest that this construction type could provide both temporary shelters and replacement low cost rural dwellings that provide a greater degree of hygrothermal comfort and improved energy efficiency. However the Chilean building regulations state that any permanent residential reconstruction receiving state funding must be constructed of a “traditional construction system” or if using a “non-traditional construction system” it must be fully certified by the Technical Department (DITEC) of the Ministry of Housing and Urbanism [17]. To receive this certification the construction system must undergo testing for fire, thermal and acoustic resistance, at a government approved laboratory according to national standards.

Despite the existence of international test results that prove an earth rendered straw bale wall can provide a fire resistance of between F60 [18] and F90 [19], a u-value of between 0.103, and 0.334W/m^{2}K [11] and excellent acoustic separation, national certified test results currently do not exist. Typically the cost for testing at the two government approved laboratories, IDIEM of the Universidad de Chile and DICTUC of the Universidad Católica, has a cost of around US$1,780 a cost not covered by government funds for reconstruction. Currently the authors are bidding for further internal funding from the Univerisdad Andrés Bello to undertake fire resistance testing at one of these laboratories.

4. APPLIED CASE STUDIES

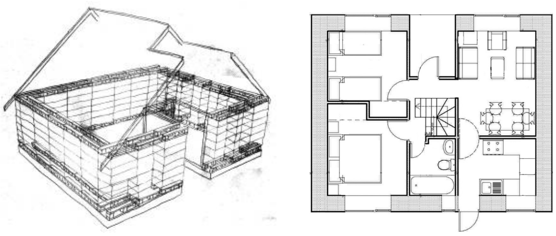
The following case studies present the intentions of local architects to use straw bales in both private and state funded reconstruction projects.

Case Study 1, Jorge Broughton Arquitectos

The Chilean architect and building contractor Jorge Broughton is experienced in building with straw bale. With more than 20 straw bale design-and-build projects completed in the last 12 years and a regular organiser of straw bale building workshops in Santiago and the Metropolitan area, Jorge is well aware of the benefits inherent in this type of construction; benefits that he believes could offer a viable solution to the rebuilding of rural communities following the earthquake. Following previous contact with the Technical Department (DITEC) of the Ministry of Housing and Urbanism whilst working on the proposals for a social housing project in Lampa, Chile, Broughton was aware of the requirements for test certificates but hoped that owing to the urgency to provide comfortable shelter following the earthquake that these requirements might be relaxed.

Following the government's call for prefabricated housing designs, Broughton designed a $60m^2$ straw bale house, with a possible additional $17m^2$ in a future first floor extension. The design envisaged the recycling of the timber from the temporary mediagua as internal partitions. The straw bales were to be rendered with a primary coat of earth render to be made from recycling adobes from collapsed houses, finished with a cement and earth top coat.

Unfortunately due to the lack of test certificates for the straw bales the design was not accepted for consideration by the Ministry of Housing and Urbanism.



Figures 6&7: Sketch and ground floor plan of straw bale single-family dwelling proposed by architect Jorge Broughton

In a parallel project Jorge Broughton has applied for funding from the government's Corporation for Production Development (CORFO) as part of their call for bids for "Innovation in Reconstruction". If successful the project will include the necessary laboratory testing to allow for the certification of straw bales construction by DITEC and a series of training workshops in rural communities in the earthquake affected regions. The aim of these workshops would be to train both self-builders and local contractors to repair traditional adobe architecture with straw bales in addition to the construction of new build rural dwellings. The results of the bid should be announced soon.

Case Study 2, Owar Arquitectos

At the time of the earthquake the office of young Chilean architects Owar Arquitectos were working in conjunction with the North American architect Evan Sellmyer Pruitt, completing the construction of a large single-family house in Coya, VI Region, Chile. The house has a timber frame in-filled with straw bales and is finished with an earth render. Except for minor cracking in the recently completed earth render around a few window openings the house withstood the earthquake undamaged. Based on this experience they too believed that straw bale could offer a solution to the reconstruction in rural Chile. In particular they were drawn to the similarity in the spatial qualities of straw bale constructions and traditional Chilean adobe architecture, qualities that they identified as important in the cultural identity of many of the affected communities. With this in mind they developed the designs for a wall prototype that could be reconstructed in place of collapsed adobe walls, with a 500mm concrete block plinth to protect the bales from ground water and large overhanging eaves or external passageways also typical feature in traditional Chilean rural architecture.

Armed with this design and the idea of building a number of prototypes that locals could copy, Owar Arquitectos approached the local councils of Lolol in the VI Region and Molina, further south in the VII Region. Due to concerns over the "un-traditional" nature of straw bale construction and inflated construction budgets from local contractors Lolol declined to pursue the project. However the meetings with Molina were greeted with an enthusiastic response and it is hoped that once the council has resolved immediate emergency issues arising in the aftermath of the earthquake, the proposals can be incorporated in the reconstruction of heritage properties that are not covered by the same Building Regulations as new build housing.

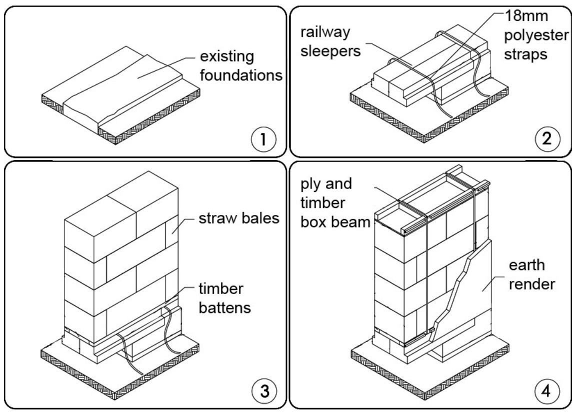


Figure 8: Construction sequence of straw bale replacement for adobe boundary wall, Owar Arquitectos

In a parallel project for a private country estate in Almahue, San Vincente de Tagua Tagua, Owar proposed the rebuilding of the estate boundary walls in straw bale on concrete block foundations, bound by nylon ties and topped with a clay tile coping (Fig. 8). The client was enthusiastic and initial material costs came in below budget. However on the receipt of tender returns from local builders it became clear that large additional costs were being added due to the "unknown" nature of the construction technique. Faced with a much lower tender return for a "traditional" fired brick option the client abandoned the straw bales. A related project on the same estate, to rebuild an historic adobe barn with straw bale, fell through when it was discovered that the client's insurance company did not insure the existing adobe constructions and refused to pay out.

5. CONCLUSION

Straw bale construction could turn agricultural waste into affordable, efficient, comfortable rural dwellings; whose thick walls and overhanging eaves reflect the traditional architecture of central southern Chile. Currently due to inexistence of national certified testing of straw bales, inexperience and lack of knowledge of the construction technique it would appear that straw bale construction will at present not play a major role in the reconstruction. However if the correct certification were to be obtained, whether through the project CORFO of Jorge Broughton, through a maintained research program by the Laboratory of Energy of the Universidad Andrés Bello or by some other means, then there will be other opportunities. Past experience has shown that reconstruction is not something immediately achieved. Five years after the last major earthquake in Chile, that of Tarapacá 2005, 10% of the rebuilding remains to be completed [20].

A recently announced relaxation of regulations for reconstruction in heritage areas could also open a possibility for the use of straw bales.

In addition, if prepared in advance, the design for a temporary straw bale shelter could offer a self-build, low cost refuge for future disasters. This could be so designed as to provide an initial refuge that would form the nucleus of a home that could grow in time.

6. ACKNOWLEDGEMENTS

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