Fire Resistance for Low-rise Housing in the Tropics: Test Results for Bamboo-based Construction Systems

Holger Wallbaum
Chalmers University of Technology

Lily Tambunan
Bandung Institute of Technology

WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

FIRE RESISTANCE FOR LOW-RISE HOUSING IN THE TROPICS: TEST RESULTS FOR BAMBOO-BASED CONSTRUCTION SYSTEMS

Corinna Salzer[1*], Holger Wallbaum[1], Lily Tambunan[2]

ABSTRACT: The use of round bamboo as load bearing member for low-rise housing is an interesting alternative construction method for tropical regions. Similar to timber engineering, a predictable fire resistance is a requirement for its legal approval and application at scale. The research presents fire test results on selected bamboo-based construction systems developed in Asia-Pacific and Latin America. Tests were conducted in Indonesia according to the *National Standard SNI 1741*, which is referring to *ISO 834-1* and *JIS A 1304*. Different bamboo wall cross-sections were tested in specimens of 1050mm by 1050mm and evaluated according to insulation, integrity and mechanical resistance criteria. All specimens received a rating of 60 minutes resistance. The research provided a general understanding of the system response and highlighted critical variables of the wall system, which can be transformed into design recommendations.

KEYWORDS: fire resistance, structural bamboo, experimental testing, low-rise housing, building system, Asia and the Pacific, Latin America

1 INTRODUCTION

In fast growing urban areas of Asia, Africa and Latin America, there is a tremendous need for cost-efficient and more sustainable construction technologies. A major share of houses is needed among low income groups, which are also disproportionately vulnerable to extreme impacts caused by a complex set of shortcomings [1], [2]. In addition, the construction sector is responsible for high global resource and energy consumption as well as waste and emission production, requiring building solutions to become more sustainable [3]. Therefore technical, economic, ecologic, and social requirements for the needed housing are high. Conventional market offerings often fail to serve this housing need: Concrete and steel based construction mismatches mostly with the affordability for low income groups. Sustainable growth mechanisms for timber are only slowly being build-up and depletion of stocks occurs, which increases the pressure on the resource timber in many emerging and developing countries. In this context, available alternative construction materials offer an interesting entry point for improvement. In tropical regions, the application of round bamboo as load bearing members for housing can be an affordable local alternative to timber, concrete, and steel.

[1] Corinna Salzer*, Holger Wallbaum, Chalmers University of Technology, Sweden, salzer@chalmers.se, holger.wallbaum@chalmers.se
[2] Lily Tambunan, Institute of Technology Bandung, Indonesia, lilyrosalina@yahoo.com

As displayed in Figure 1, bamboo is a rapidly renewable raw material, which can be found between 50° North and 47° South latitude around the world [4], [5].

Figure 1: *Global Bamboo Distribution* [4]

Remarkably, countries in which bamboo exists are often times also the ones with highest urban population growth rates and housing backlogs. Due to the annual reproduction of bamboo poles, and a matureness for structural application reached in only 3 to 5 years [6], [7], the boundary conditions for sustainable supply chains without depletion of existing stocks are good. Given its availability and affordability, bamboo has been used traditionally in many cultures. As the hollow tubular shape of bamboo is naturally suited for high load transfers along its grain, one of the existing applications for round bamboo is housing. However, for example in Asia and the Pacific, bamboo-based houses are mostly found in rural areas in which bamboo is exposed to sun and rain as element of the outer building envelope [8]. In contrast to timber engineering, where surface deterioration of a solid timber can be accounted for in the structural design of the cross section, the deteriorated of thin walled bamboos with a fixed cross section might mean a critical loss of structural stability.

Only few traditional and modern building methods using structural bamboo have considered durability, technical reliability and compliance to construction regulations in their development stage. These aspects are necessary performance indicators in the urban housing field, in which a reliable building performance has to be ensured to policy makers, loan providers and potential house owners accepting long term financial commitments. To transform a none-specified raw material into a reliable building system for the urban housing market, traditional knowledge has to be supplemented with research and development tackling open questions for a standardized construction. In the last two decades research and application has successfully delivered some answers , for example in the fields strength grading of selected bamboo species, development and testing of connection types, design of specific details and conceptualization and testing of cost-efficient, durable building methods able to resist local design impacts. In some countries of Latin America and Asia such as [9]–[11] this development has led to Building Codes for bamboo or to legally approved housing projects [12]. Even a first international standard on structural design was implemented [13].

This research focuses on such a technically refined and tested building system described as *Cement-Bamboo Frame System* and as constructed by [12]. The described building system is rooted on practices in Latin America [9], [14] and got refined for an application in Asia through standardization and prefabrication concepts, as well as an inclusion of traditional practices and innovative ideas in the Philippines [8]. A short introduction to the constructive system is given in the following to derive its relevant performance characteristics. The structural system is shear walls containing two main components: a shear resisting frame and a wall cover. The shear frame is made-up of bamboo and wood, with metal or bamboo bracing and metal-mortar connections. Horizontal timber rails at the bottom and top and vertical bamboo studs are connected through metallic anchors. Diagonal flat bars or bamboos are used as braces to resist lateral forces. The cover of the frame is characterized by the plaster carrier, the plaster and its anchorage system onto the shear frame. For all three variables, several configurations can be found. The plaster carrier, for example, can be made from a bamboo brought into a flattened shape, a wood sheeting on which surface a wire mesh is fixed for cohesion and crack reduction of the plaster, or an expanded metal mesh. The plaster carrier is fixed to both bamboo studs and timber rails of the shear system and contributes to the stiffness of the system. The anchorage of the cover onto the shear frame is realized through common nails or screws. The plaster itself can be of different mixture and thickness and contain additives or not. The components of the system are visualized in Figure 2.

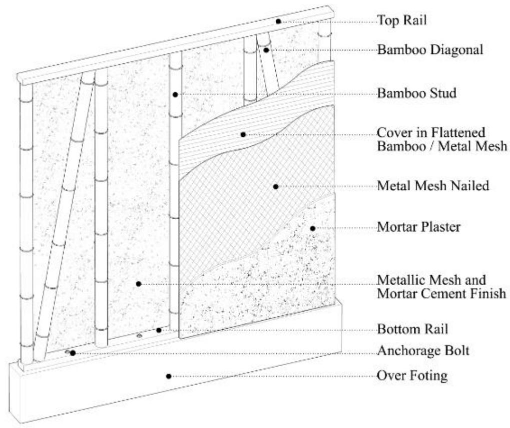
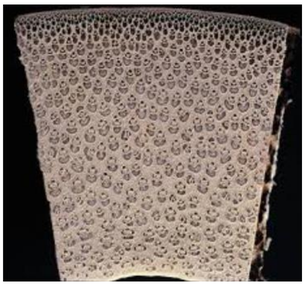


Figure 2: *Cement-Bamboo Frame System* [14], [15]

The design loads considered in the technical development of this building system includes extreme impacts such as earthquakes, typhoons, flooding and fire impact. The compliance to fire safety standards is a must-have criterion for all urban settlements, while the occurrence of earthquakes, typhoons and flooding varies regionally, but commonly occurs in the Philippines, where [12] is building houses.

Fire resistance was long a major barrier for the scale-up of timber engineering [16]. The need for a predictable and safe building response under fire impact was motivation to conduct research over the last decades and finally overcome this barrier [17]. For bamboo-based building systems it is similarly critical to develop and prove functioning concepts in order to approve the raw materials usage for construction. First results on the fire resistance for round and laminated bamboo were obtained by [18] for the bamboo species Gudaua Angustifolia Kunth sourced in Colombia. The study looked at the properties heat flux, flame spread, and charring rate. The ignition critical heat flux was found to be 14 kW/m^2, both for round and laminated bamboo specimens, compared to a reference value of 11kW/m^2 for plywood. Round bamboo resisted ignition longer than laminated products and fame spread was identified comparable to wood products. A charring rate of 0.24mm/min was determined, which is clearly lower than sources state for solid hard and softwood ranging from 0.55-0.80mm/min as published by [19]. The study for bamboo on material level concludes that performance indicators on fire reaction and fire resistance are comparable or better than wood and a favorable fire behavior exists. As a reflection on this study, it can be said that the late ignition of round bamboo can be related to the high silica content of fibres in the bamboo skin. Since the inner wall of bamboo has different amount of fibers and matrix, a change in charring rate from outside to inside is likely. It is yet to be tested that the initial ignition is delayed, while an acceleration in charring rate over time is to be expected towards the inside of the bamboo pole. Further testing on material level is recommended to verify the results of [18] including consideration of other bamboo species to ensure conservative assumptions for the design of bamboo-based structures.



Picture 1: *Close-Up of a Bamboo Culm Cross Section* [20]

Fire impact remains to impose a more critical challenge for round bamboo due to its hollow shape and thin walls of 8-12mm. In timber construction a solid cross section can be designed according to the required fire resistance level. For bamboo, independent of a late ignition and a favorable charring rate, once ignited it will decrease the fixed cross section sensitively setting its structural performance and the minimum penetration depth of anchors for the separating cover at risk. This is especially valid when looking at resistance level for houses of 60 minutes, being a requirement in many bamboo growing countries. As the raw material itself cannot sustain such durations, a protection of round structural bamboo is needed to prevent direct fire exposure. While laminated bamboo enables the design of cross sections according to minimum structural needs, similar to solid and laminated wood, the production requires industrially advanced facilities. Logistics, financial investments and a stable quality control are often times not available in many bamboo growing countries. Therefore the focus of this paper remains on the research question of fire resistance for round bamboo used in building systems for housing.

A protection of the structural elements can be obtained, among others, through the application of fire retardants on the structural members or sandwich wall cross sections in combination with further building materials. In [21] the effect of fire retardant on industrially processed bamboo products was assessed. Similarly to timber engineering it was found that the method of application and the type of retardant itself has an impact on both physical and mechanical properties of the laminated bamboo products. The identification of correction factors is needed for proper consideration of the usage of retardants in structural design. Retardants on round bamboo have not yet been evaluated and need to consider the challenge of bamboos smooth outer skin. Latter will limit the suitability of existing products from the timber sector due to reduced penetration and cohesion properties. While reducing the bamboo skin to enable penetration and cohesion, it goes in line with removing the natural silica protection of the skin too. Besides technical considerations, also economic and ecologic considerations have to be included in such an assessment. A sandwich application has been assessed by [22], using laminated bamboo panels. The evaluated wall cross section was composed of a 10mm laminated bamboo panel placed on the fire none exposed side, 84mm heat insulation material and a 10mm gypsum panel on the fire exposed side. A temperature on the unexposed side of below 84°C and no charring of the bamboo product was enabled through the protective function of the gypsum board as well as the insulation material. A one hour fire rating of the structure was obtained. However, given load bearing function of the wall section is wanted, fire exposure from two sides has to be assumed and an additional mirroring of the sandwich layers would be required. Further findings of the testing were: local smoldering, as occurred over 12 hours for the test specimen, highlights the relevance of proper fire extinguishing to avoid loss of integrity over time and full scale testing has the advantage to visualize effectively weak construction details, in this case, openings of the building envelope, which can lead to early ignition at such details.

The fire resistance of building systems using round bamboo as structural members has not yet been studied. The research evaluates performance of wall elements of the Cement-Bamboo Frame System introduced above under impact of fire. With this, the paper contributes to the research gap of unlocking the material round bamboo for the global housing needed.

This study tested fire resistance of the Cement-Bamboo Frame System in Indonesia. With more than 250 Mio inhabitants, Indonesia experiences rapid urban growth [2]. Further, a scarcity of timber, an abundance of not fully exploited bamboo, as well as a test stand for fire testing, made it an interesting sample case. As implementation reference of the building system, the sizable application by [12] in the Philippines was taken, as visualized in Picture 2/3, where no test stand exists.

Picture 1: *Structural System implemented by BASE* [12] *in a cooperation project with* [23] *in Iloilo | Philippines*

Picture 3: *Completed house as implemented by BASE* [12] *in a cooperation project with* [23] *in Iloilo | Philippines*

Several countries in Asia-Pacific, such as Vietnam, Thailand, India, Bangladesh or Nepal are possible further possible transfer countries with similarly a high need for affordable housing and underutilized bamboo potential. The building system has therefore a large potential to be transferred to other countries, given specific local cultural needs and design impacts are adjusted.

2 MATERIALS AND METHOD

For evaluating the fire resistance of the Cement-Bamboo Frame Building System, *experimental testing* was chosen. In the following the materials, test method and specimen design are described with more detail:

Materials
The specimens for testing used the bamboo species *Gigantochloa Apus*, available and common in Java, Indonesia. Java, the island of Indonesia with the largest population of approximately 145 million inhabitants is an attractive housing market [2]. The bamboo species was chosen because of its structural characteristics, its affordability and availability in Java. *Gigantochloa Apus* has a typical diameter of 80-100mm and a minimum wall thickness of 8-12mm in the structurally deployed part of the bamboo pole. Its mechanical properties have been identified by [24]. An available, affordable, structural species in a highly populated area ensured the significance of the selection.

Method
Systemic fire research distinguishes between testing on member, part and building level, as visualized in Figure 3. This paper has conducted experimental fire testing of *wall elements* of the *Cement-Bamboo Frame System* and is therefore on the level of components or parts.

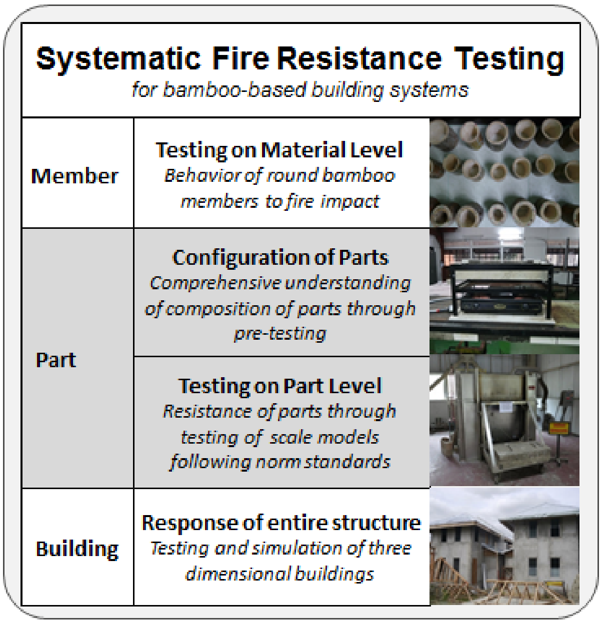


Figure 3: *Systematic Fire Research on Member, Part and Building Scale highlighting part level focus of this study*

Through configuration testing, variables of the wall system were understood in-depth. A detailed description of the results is subject to a more comprehensive publication. This paper mentions the evaluated variables and summarizes key findings for norm testing on part level. Assessed variables were: (1) Effect of fire retardant on round bamboo, (2) Anchor options to fix protective cover in bamboo, (3) Type of plaster carrier, (4) Plaster thickness, (5) Plaster composition, (6) Usage of additives in plaster, and (7) Existence of one or two layers of the protective cover. Based on the results of pre-testing, two recommended wall configurations were derived. Latter were tested in standardized experimental tests following the National Standard of Indonesia *SNI 1741: Testing method of fire resistance for structural components in houses and buildings* [25]. The standard was developed by the Indonesian Government and refers to two acknowledged fire standards being *ISO 834-1: Fire resistance tests - Elements of building construction* [26] and *JIS A 1304: Methods of fire resistance test for structural parts of buildings* [27]. The furnace temperature curve of SNI is similar to ISO. Time for fire exposure was 60 minutes being an accepted resistance standard in many countries of bamboo growth.
As the assessed wall system is load-bearing, its mechanical resistance under fire impact is important. The separating function of the wall system is further essential to prevent fire spread in dense urban settlements. In the following, it is referred to three performance categories as introduced in [25]–[28]: Insulation (I) and Integrity (E), both needed for the separating function of systems, and Mechanical Resistance (R) for its load-bearing performance. As measure for insulation, the temperature increase over time on the unexposed side of the construction was evaluated. The integrity criterion is visually assessed

through the aspects surface damages and flame spread at the unexposed side during the testing. The mechanical resistance is ideally evaluated during testing. As the test stand had no option to test under load, a process along of recommendations of [28] was implemented as described below:

1. Observed charring depth of structural member after fire testing
2. Assessment according to the reduced cross section method with the effective cross section being the residual cross section minus areas of zero strength and stiffness.
3. Verification of performance in separate testing of the structural members extracted after fire testing with reduced mechanical properties.
4. Decision of sufficient load bearing capacity according to: $E_d < R_d$

Specimen Design

Variables investigated under the configuration phase and fixed for the norm testing are summarized below:

- Plaster thickness: The cement plaster acts as fire protection material. Its thickness is critical for the protection time and was designed according to protective function needed to maintain a minimum allowable bamboo cross section after 60 minutes of fire exposure. The failure time of protection is assumed through simplified factor of 1.4 multiplied with the thickness in mm as suggested in [28]. To balance protective function with dead weight of the plaster, a 25mm plaster was applied.
- Plaster composition: A standard plaster mixture was chosen without use of additives.
- No fire retardant on round bamboo: The surface treatment of bamboo has indicated positive effects, but requires more in-depth studies. For the norm testing it was therefore excluded.
- Standard anchors: To fix the cover in the structural bamboo, common nails were used. Special screws or anchors were excluded to reflect the most conservative, affordable and simple specimen configuration.

Variables varied in the norm testing:

- Type of plaster carrier: A common organic plaster carrier made from bamboo and a metallic plaster carrier was tested. Both are flexible to accommodate for diameter differences of the round bamboo ensuring a straight wall finish.
- Existence of one or two layers of protective cover: As load bearing construction elements shall be designed for fire exposure from both sides at the same time, specimen were designed with protective cladding from both sides. However the affordability requirement motivated the testing of an economic configuration using a single layer cladding only. Latter was tested to account for a conservative initial state, which is meant to be upgraded afterwards to two layers.

The above mentioned variables led to four wall cross sections tested as summarized in *Table 1*.

Table 1: *Summary of test specimen, 2nd Phase*

ID	PLASTER CARRIER	COVER
1	Type A: Organic	One layer
2	Type B: Metallic	
3	Type A: Organic	Two layers
4	Type B: Metallic	

All layers of the wall cross section were considered with their position in the assembly to reflect on the separating function. Specimen of the size 1050mm by 1050mm were produced as displayed in *Figure 4-6* and *Pictures 4/5*.

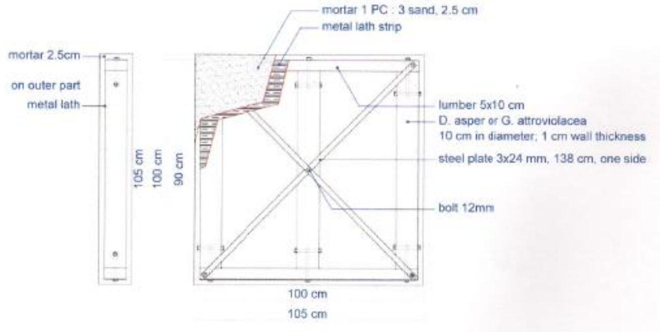


Figure 4: *Specimen design for fire testing- Constructive Details for specimen with metallic plaster carrier*

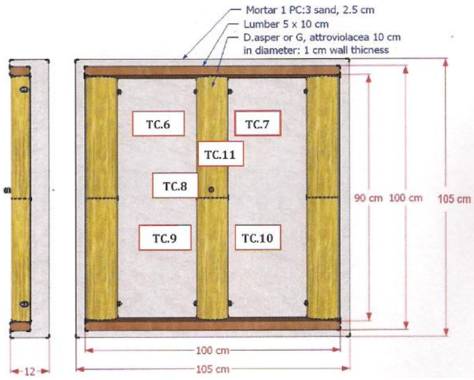


Figure 5: *Specimen design for fire testing- one layer of protective cover*

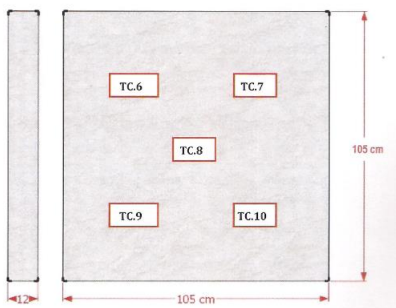


Figure 6: *Specimen design for fire testing- two layers of protective cover*

Test Facility

The test facility used was the *Research and Development Center for Housing and Settlements* in Bandung / Java, Indonesia [29]. The facility conducts accredited fire testing for approval in Indonesia. Researchers at [29] were further in charge in formulating the SNI standard. Pictures 4/5 show the furnace in the test facility, Picture 6-8 the installation of the specimen with thermocouples at the furnace prior to testing.

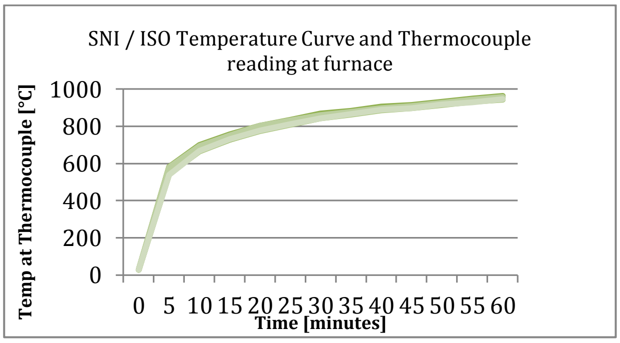
Pictures 4/5: *Furnace for testing fire resistance at* [29]

Pictures 6/7: *Installation of specimens prior to testing*

Picture 8: *Specimen with thermocouples prior to testing*

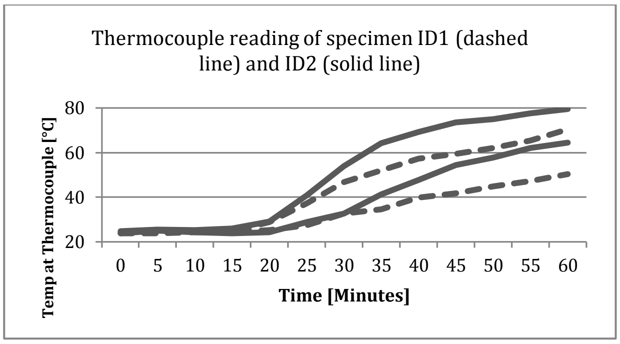
3 RESULTS

The results obtained after the one-hour fire impact are presented according to the categories Insulation (I), Integrity (E) and Mechanical Resistance (R), as required for elements with separating and load-bearing function. The thermocouple readings at the furnace during testing provide evidence that the temperature curve of SNI / ISO was followed with sufficient precision during the whole testing period of 60 minutes, as documented in Graph 1.



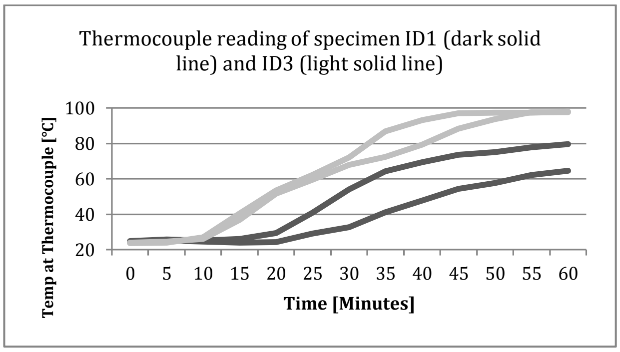
Graph 1: *Temperature Curve of SNI / ISO standard and furnace temperature recorded during testing*

Insulation (I): Graph 2 displays the temperature increase over time on the unexposed side of the construction. All tested specimens received an insulation fire rating of 60 minutes. Maximum reading of a thermocouple at the fire unexposed side was 80°C after 60 minutes, with other thermocouples ranging from 50°C upwards depending on the thermocouple location. 80°C is clearly below maximum allowable temperatures according to norm of 140°C (average) and 180°C (max). Graph 2 shows the maximum and minimum thermocouple reading for specimen ID1 (organic plaster carrier) and ID2 (metallic plaster carrier). Specimen ID1 had an additional insulating effect compared to ID2 as well as a less rapid temperature rise due to the insulating effect of the organic plaster carrier. Given that both specimens performed sufficient, insulation was not deemed a critical variable for the wall system.



Graph 2: *Min / Max thermocouple reading of specimen with organic and metallic plaster carrier*

Specimens ID3/4 were more conservative in comparison to ID1/2 in regards of their insulation properties. Temperature readings increased more rapid and already after 10 minutes of testing, while ID1/2 specimens only showed temperature rise after 20 minutes. A maximum temperature of 100°C after 60 minutes was obtained. Since the results for ID3/4 specimens remained in allowable temperature range, it was assessed uncritical provided that the specimen with one layer protection is exposed to fire from its protected side. The behaviour of specimen ID1/3 is displayed in Graph 3.



Graph 3: *Test reading of thermocouples of selected specimen during testing*

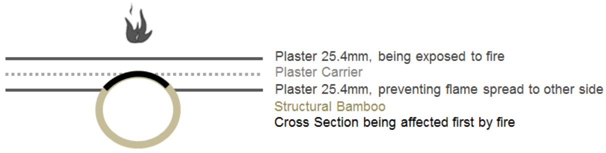
Integrity (E): The integrity of all specimens was maintained during the period of testing. No flame-spread on the fire unexposed side occurred, neither for specimen ID1/2 nor for ID3/4. An assessment of the fire-exposed and unexposed surfaces during and after the testing indicated however a different behaviour between ID1/3 and ID2/4 respectively. Under impact of fire, the specimen ID1/3 encountered strong cracking and partial flaking of plaster portions. The occurrence of wider cracks at the fire exposed surface increased the risk of linear heat peaks. Both effects were significantly reduced with specimens ID2/4. The visual assessment of the crack pattern and crack width indicated less cohesion between the organic plaster carrier and its plaster cover. **Error! Reference source not found.**s 9/10 show left specimen ID1 and right specimen ID2. The appearance of cracks was also observed during the testing from the fire unexposed side of the specimen, as shown in Picture 11.

Pictures 9 / 10: *Visual assessment of Surface Integrity after Testing of two specimens with different plaster carrier, left: organic, right: metallic*

Picture 11: *ID3 specimen with organic plaster carrier during test when cracking of protective cover occurred*

For the specimen ID3/4, where structural bamboos are unprotected at the unexposed side, the existence of a plaster layer at the unexposed side was an important feature to suppress flame spread and fulfil integrity criterion. In that way, no flame spread occurred during 60 minutes although the structural bamboo partially started to be affected by fire from the exposed side (Graph 10).

Pictures 12 / 13: *ID3/4 specimen after testing on unexposed side*



Graph 2: *Schematic drawing showing effect of plaster layer on fire unexposed side of specimen*

Most critically, it has to be mentioned that possible effects of reduced penetration depth of anchors holding the cover due to starting charring of the bamboo were less visible when testing without load and only a post testing assessment enabled its evaluation. According to [28], a minimum anchorage penetration of 10mm is required for timber structures. If this requirement is followed for bamboo with a typical bamboo wall thickness of 10mm, any kind of charring would be equal to a failure, although structural capacity would allow for a reduced cross section.

Mechanical Resistance / Stability:

The mechanical resistance of the wall system during fire exposure is needed to maintain its load bearing function. Therefore the time of fire resistance with regards to load bearing function was evaluated. Since the test stand at [29] did not provide testing under load, the mechanical resistance was assessed through determination of the effective cross section of bamboo after 60 minutes fire exposure. Although different levels of charring were identified for specimen ID1/2 and ID3/4, from no charring to punctual 5mm of charring, the load bearing capacity of bamboo poles after fire impact remained sufficient according to the criterion $E_d < R_d$ and the reduced cross section method introduced in Section 2. A detailed classification of the degrees of charring obtained for all specimen and calculations of the respective effective cross-sections are subject to a comprehensive publication.

Picture 14: *Removal of protective cover to assess residual bamboo cross-section after fire exposure of 60 minutes*

Picture 15: *Classification and systematic assessment of degree of charring on structural bamboo*

The organic matter of specimen ID1/3 caused longer smoldering periods and enabled flame spread across the wall. Both characteristics are a critical risk factor for the mechanical resistance of the wall assembly and favour specimen ID2 over ID1. For specimen ID1/2 a second layer of 25mm plaster enhances the compartmentation, however, since structural bamboo in the wall center starts charring after the failure time of layer one, the second layer acts only for fire protection from both sides of the walls, but does not increase the protective function.

4 CONCLUSIONS AND RECOMMENDATIONS

Fire resistance is a critical requirement for building technologies using organic structural members. This paper assessed the fire resistance of an alternative construction technology using shear frames made of round bamboo and timber. Due to the hollow shape and thin walls of bamboo members, the fire resistance of bamboo walls has to be obtained through a protective cover. In case of the evaluated building method, this is a cement based cladding fixed to the structure on a plaster carrier. With a target resistance of 60 minutes, the configuration of the cover was a key factor for sufficient protection of the structural members. Through experimental fire testing a recommendable system configuration was derived and relevant criteria determined, such as (1) Usage of favorable plaster composition limiting cracking and crack width on the plaster surface of walls, (2) Usage of a plaster carrier with good cohesion to plaster and minimal flame spread during fire exposure, (3) Application of plaster on fire unexposed side to avoid flame spread in case of interior bamboo exposure and (4) Anchorage system ensuring performance of protective cover in limited wall thickness of bamboo. For all specimens, insulation performance was good. For integrity performance, the metallic plaster carrier performed better than the organic one. For the mechanical resistance, charring of bamboo has to be prevented completely to ensure compliance to minimum penetration depth of anchors holding the protective cover in the bamboo. A detailed assessment of the mechanical resistance of bamboo poles after fire exposure showed, on the other hand, that initial charring after failure of the protective cover does not set the load bearing capacity of the system at risk immediately and could possibly be considered for the system performance. Further studies to determine necessary safety factors and reduced mechanical properties for structural bamboo are recommended.

In addition to the active resistance of the building system, a passive protection through risk reduction is recommended for bamboo-based housing projects. Structures using round bamboo for load transfer are to be embedded in a holistic fire safety concept, including set-backs between houses, minimum requirements for safe electrical wiring, behavioural trainings for inhabitants and a general firefighting concept for settlements with a relevant share of houses made from organic matter. Finally, holistic fire safety concepts have to consider realities in settlements of rapidly growing urban centers in Asia, Latin America and Africa.

A Structural Fire Design for bamboo-based structures is recommended for the future, which allows the calculation of design strenght and stiffness of wall elements under consideration of a partial safety factors for bamboo in fire and the determination of a modification factor for fire. Since research about the fire resistance of bamboo-based housing is a rarely touched field, the paper highlights fields for further scientific attention:

- Deepen the assessment of the stability criteria for specimens: Through testing at facilities with ability to test under load or a systematic assessment of bamboo cross sections and load bearing capacities, leading to the formulation of modification factors for mechanical properties and partial safety factors for bamboo in fire.
- Design of connections and anchorage systems in bamboo for effective fixture of protective cover

onto the shear wall frames during fire impact. Further, detailing of connections between wall to roof, wall to intermediate floor, fire walls between housing units etc.

- Verification testing of [18] on member level for ignition time and charring rates, as these are critical variables for the performance of combined systems and needed to predict bamboo in a conservative manner.
- As recommended by [28] and conducted in [22], effective fire design is based on a combination of tests, simulation and calculations allowing the calibration of thermal properties to test results. Doing so on building scale enables to see the combined action of parts as well as weaknesses.
- Assessment of the smoke spread of bamboo and bamboo based houses.
- Assessing the transferability of research results across bamboo species of structural grade as well as varying growth regions to increase significance of the research findings. Latter includes a comprehensive review of building standards such as Eurocode, ISO, JSP, SNI and others, to understand comparability of test results, where needed.
- Research on more building systems, larger structures and/or settlement level.

ACKNOWLEDGEMENT

Acknowledgement is given to Base Builds, an initiative of Hilti Foundation on sustainable and resilient housing, which funded this research. Further acknowledgement is given to the Research and Development Center for Housing and Settlements (PUSKIM), where SNI tests were conducted. Thanks are also extended to Dr. Ing. Andry Widyowidjatnoko, Rakhmat Aditra, Dibya Kusyala, and Ir. Ginandjar as extended research team of ITB.

REFERENCES

[1] UNEP, *Sustainable solutions for social housing: Guidelines for project developers*. 2013.

[2] UN-ESCAP and UN-Habitat, *The State of Asian Cities 2010/2011*. Bangkok: United Nations Human Settlements Programme; United Nations Economic and Social Commission for Asia and the Pacific, 2011.

[3] UN Habitat, “Green Building Interventions for Social Housing,” 2014.

[4] INBAR, Y. Yang, C. Hui, and F. Du, “China`s bamboo (eds) culture/ resources/ cultivation/ utilization,” Beijing, 2010.

[5] M. Lobovikov, S. Paudel, M. Piazza, H. Ren, and J. Wu, “World bamboo resources,” 2005.

[6] International Network for Bamboo and Rattan, *The Climate Challenge and Bamboo: Mitigation and an, International Network for Bamboo andAdaptation*, vol. 86. 2011.

[7] E. R. Barile, *Monograph on Production and Utilization of Philippine Bamboos*. Los Banos: Forest Products Research and Development Institute, 2007.

[8] C. Salzer, H. Wallbaum, L. F. Lopez, and J. L. Kouyoumji, “Sustainability of Social Housing in Asia : A Holistic Multi-Perspective Development Process for Bamboo-Based Construction in the Philippines,” 2016.

[9] AIS, “NSR-10: Section E: One and two-story structures from Bahareque,” Bogota, 2009.

[10] Government of India, “National Building Code of India,” 2005.

[11] Inbar Latin America and MHCS, “Peruvian Technical Norm NSR- 1, Title E: Bamboo,” Peru, Lima, 2009.

[12] Base- an initative of Hilti Foundation, “Base-sustainable and resilient social housing in the Philippines,” 2015. [Online]. Available: http://www.base-builds.com/. [Accessed: 30-Nov-2015].

[13] ISO International Organization for Standardization, “ISO 22156 - Bamboo - Structural Design,” 2004.

[14] Inbar LA, “Peruvian Technical Norm NSR-1, Title E: Bamboo,” Peru, Lima, 2009.

[15] Base for ASEP, “DRAFT: NSCP Vol.3 - Housing. Chapter: Bamboo,” 2016.

[16] B. Serkov, *Fire Behavior and Fire Protection in Timber Buildings Springer Series in Wood Science*. .

[17] B. Östman and B. Källsner, “National building regulations in relation to multi-storey wooden buildings in Europe,” *SP Trätek Växjö Univ. Sweden*, pp. 1–26, 2011.

[18] J. Mena, S. Vera, J. F. Correal, and M. Lopez, “Assessment of fire reaction and fire resistance of Guadua angustifolia kunth bamboo,” vol. 27, pp. 60–65, 2012.

[19] A. Frangi and M. Fontana, “Charring rates and temperature profiles of wood sections,” vol. 102, no. March, pp. 91–102, 2003.

[20] W. Liese, “The anatomy of bamboo culms,” *Tech. Rep. No. 18*, 1998.

[21] D. Chungui, J. Song, and C. Yongxing, “The effect of applying methods of fire retardant on physical and mechanical properties of bamboo scrimber Chungui Du,” *Adv. Mater. Res.*, vol. 1048, pp. 465–468, 2014.

[22] Y. Xiao and J. Ma, “Fire simulation test and analysis of laminated bamboo frame building,” *Constr. Build. Mater.*, vol. 34, pp. 257–266, 2012.

[23] Homeless People`s Federation of the Philippines, “HPFPI,” 2013. [Online]. Available: http://www.achr.net/index.php. [Accessed: 30-Nov-2015].

[24] Base and Institute of Technology Indonesia, "Physical and Mechanical Properties of Gigantochloa Apus Bamboo," Bandung, 2016.
[25] SNI, "SNI 1741-2008: Testing method of fire resistance for structural components in houses and buildings," 2011.
[26] ISO International Organization for Standardization, "ISO 834-1 Fire-resistance tests- Elements of building construction- Part 1: General Requirements," 1999.
[27] JIS Japanese Industrial Standard, "JIS A 1304 - Method of fire resistance test for structural parts of buildings," 2011.
[28] Eurocode 5: EN 1995-1-1, "EN 1995-1-1:2004 Eurocode 5: Design of timber structures- Part 1-1: General - Common rules an rules for buildings," 2004.
[29] PUSKIM, "Research and Development Center for Housing and Settlements," 2015. [Online]. Available: http://puskim.pu.go.id/, Retrieved 20.09.2015. [Accessed: 20-Nov-2015].