Codes and standards development for nonconventional and vernacular materials

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Chapter outline

4.1 Standardization as *lingua franca*

In the context of civil infrastructure, conventional construction materials such as steel, timber, and reinforced concrete were once unconventional and unproven materials. Acceptance was achieved through decades of testing, analysis, and experience which evolved into standardized building code practices (Box 4.1). Even today, the

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Box 4.1 Definitions of terms used in the context of this chapter

Standard — A generic term encompassing consensus documents that include test methods, practices, specifications and model codes.

Specification — A detailed description of material and geometric properties of a material or product. Specifications will typically be cited in contract documents in addition to model codes.

Model Code — A consensus document intended to provide minimum requirements that must be met in the construction of buildings. Model building codes are developed and maintained by a standard-writing organization independent of the jurisdiction(s) responsible for enacting the building code. Model codes will typically cite various standards and specifications as evidence of compliance with provisions of the Code.

Building Code — A series of ordinances enacted by a jurisdiction or entity establishing minimum requirements that must be met in the construction of buildings. Building Codes are conventionally model codes adopted with or without (locally relevant) revisions.

Characteristic Value — A value of a material property obtained from statistical evaluation of test data. Characteristic values are given in terms of a specified variation from the mean expressed with a given confidence. Typical examples of natural (bamboo, earth) and engineered (FRP) materials are given below:

Example material	**Characteristic value (assume n = 25)**		**Probability test value will exceed characteristic value**
	Typically expressed as	**Equivalent to**	
Bamboo[1]	5th percentile capacity expressed with 75% confidence	Mean value minus 1.9 standard deviations	87.0%
FRP reinforcing bars[2]	Mean value minus 3 standard deviations	5th percentile capacity >99% confidence; or 1st percentile capacity >95% confidence	99.9%

[1]ISO 22156 and 12122.
[2]ACI 440.1R-15.

standardization of these materials continues to be refined through the work of universities, laboratories and professional organisations. More recently, standardization of materials that are still considered to be unproven has been emerging. For instance, fiber reinforced polymer composites, which were initially developed for aerospace applications, are being standardized for use in civil infrastructure and, as a result, their use is burgeoning. Natural building materials such as bamboo, earth, and straw bale construction are also receiving increased interest in terms of standardization, leading to their acceptance internationally and their emergence as “new” products. Nevertheless, the standardization of nonconventional and vernacular materials is still in its earliest stages; design, construction, testing protocols and technical terminology, even among experts, are fragmented and requires further evolution.

The importance of nonconventional and vernacular materials and practices standardization lies in both technical and social realms. The objective of a standard material test procedure, for instance, is to accurately determine a design value for the material (e.g., a strength or a stiffness) as well as to provide a common frame of reference for the user community − a *lingua franca* of sorts. Data from such comparable tests can be compiled to obtain a more reliable understanding of a material’s properties based on a statistical analysis which can lead to the refinement of, and confidence in, design values. This, in turn, leads to broader acceptance of the material in the design community. Such acceptance, coupled with advocacy, can lead to broader social acceptance of previously marginalized vernacular construction methods (Harries et al., 2012).

4.2 Material standard versus standard material

In many cases of conventional construction materials, engineered materials specifications (or standards) result in standard (or standardized) materials and building products. However, when it comes to nonconventional and vernacular construction materials, the emergence of standard materials from engineered building standards is often challenged by their high variability and their reliance on local or traditional construction methods.

Ritchie (2011) describes the design of engineered structural materials a problem of balancing two (mostly) mutually exclusive material and structural properties: toughness (meaning ductility and resilience in this context) and strength. “Strong materials are inherently brittle [non-ductile] while tough materials are usually weak.” (Ritchie, 2011) The evolution of modern structural steel, which exhibits both strength and ductility, is an illustration of this dichotomy and the role which material standards play in addressing it (see Box 4.2). The evolution of standard products from material specification “recipes” is largely a product of industrialization and benefits from the quality control available to such processes.

Most nonconventional and vernacular materials are natural, rather than man-made. Materials are locally sourced and often processed or mixed on site as they are required. The degree to which the end-use construction products are engineered from these materials varies although the natural material remains the ‘feedstock’ and is the focus of this discussion of materials standards and specifications. Unlike conventional engineered materials which are developed through the “formulation and synthesis of new compounds with structural control primarily at the micrometre scale” (Wegst et al., 2015), natural materials are typically comprised of a few components having relatively poor intrinsic properties. The superior properties of natural materials result from the complex architecture of the material over a variety of length scales

Box 4.2 Evolution of modern structural steel

Pure iron is an inherently soft material; it is easily formed and quite ductile. The addition of carbon into the melt furnace imparts rigidity to the iron crystal structure resulting in a stronger although more brittle material. Modern steel evolved from cast iron (having 2.5%–4% carbon content, it is sufficiently strong for structural applications but very brittle), through wrought iron (less than 0.1% carbon having improved strength and ductility but poor interlaminar strength), to Bessemer steels (improved orthotropic strength and ductility), and finally to the strong and ductile low-carbon (0.23%–0.30% carbon) steels of today. The chemical composition of modern steel materials is standardized through material specifications and indeed there is a codex of sorts that identifies equivalencies across international standards in the form of the *Universal Numbering System* (in North America) and the *EN* (European Norm) numbering system. Structural steel chemistry imparts strength, ductility, toughness, weldability and corrosion resistance and each trait affects the performance of the others. As a result, there are many different structural steel material specifications, each intended for a specific end use. Since steel is a man-made engineered material, this poses no real impediment: each standard simply represents a different 'recipe' in the charging furnace; consistency and reliability (a *lingua franca*, as it were) is assured in this manner. As an example, the specified chemistry of two types of steel reinforcing bars differ only in their upper limit of phosphorus: ASTM A706 is limited to 0.035% whereas ASTM A615 is limited to 0.060% by weight. This difference makes A706 weldable (A615 is not) and tighter control on yield and tensile properties makes it also appropriate for seismic applications.

(Wegst et al., 2015). Natural materials have evolved (or have formed) to represent a "local optimum for a given set of requirements and restraints"; for biological materials, these include both mechanical and biological functions (Wegst et al., 2015). These requirements are usually different from the engineering uses to which we apply the materials. For example, bamboo has not evolved to accept penetrations for bolting pieces together while steel has been engineered to be bolted. Similarly, unmodified clay-based materials are not inherently stable when formed into rectangular blocks while concrete has been engineered to be placed in to forms.

Natural materials are also highly variable. For instance, for *Guadua angustifolia* bamboo obtained from three different regions of Colombia, the coefficient of variation of reported material properties uniformly exceeded 40%, reaching above 60% in some cases (Lozano, 2010). In the National Building Code of India (NBCI, 2005), reported elastic modulus values of bamboo vary by a factor of six from species to species. Similarly, the coefficient of variation of reported tensile strength of fibers used in different earthen cob mixtures (comprising clay, sand, and straw) made by local builders was 59%, and the plasticity index of these mixtures showed a 67% coefficient of variation

(Pullen et al., 2011). These results illustrate the dependency of material properties on local resources, and their efficient and safe use on local tradition and expertise.

Such variation affects both the construction process (e.g., workability, drying time) and the building outcome in terms of structural performance. This makes it challenging to develop materials standards having the same objectives or formats as those used for engineered materials. Large variations in material properties leads to smaller characteristic strength values. For bamboo, for instance, it is typical to define the characteristic strength as the fifth percentile capacity expressed with 75% confidence (ISO 22156-2004; AIS, 2010) – at best (large sample size), this equates the characteristic strength to being the tested mean strength minus 1.7 standard deviations. This characteristic value is then subject to factors associated with in situ conditions and use (such as, environmental and load duration factors) in addition to more general "factors of safety". The result is a design strength on the order of 15% of the mean strength determined from material testing (ISO 22156). This reduction means that the material is not efficiently utilized making it, potentially, unattractive to engineers who must consider both monetary and environmental cost of their structures. Furthermore, due to their variability, and in order to verify their code compliance, natural materials require field tests that are often easy to perform, but are limited in terms of their accuracy. Due to the high variability, in order to maintain a desired confidence, frequency of field testing is also higher than for engineered materials.

The challenge of material variation could be addressed by various strategies. For instance, wood is a natural building material that exhibits large variability, yet we develop both prescriptive and performance standards for timber. This has led to agreement on standard lumber products, and to the use of wood as one of the main building materials in one of the heaviest regulated environments - North America. While the number of wood species is great, the main strategy used in timber standardization is to group species according to their structural properties and appearances, prescribing uniform grade-use data for each group.

4.3 The 'cart and horse'

Construction design standards do not exist in a vacuum; at a minimum, they rely on materials specifications which, themselves require test standards. For example, design equations provided for column buckling (say) not only inherently include the likely impact of erection tolerances specified in the design standard but also of member and material tolerances provided in materials specifications. This leads to a number of issues when considering nonconventional and vernacular materials. Unlike for engineered materials, materials specifications do not exist for nonconventional and vernacular materials; there is no recipe. Thus the design standard must account for the variability in the material without having any quantification of this. Materials specifications are difficult to establish since there are no 'standard' materials and no design basis to which to aspire. Design standards and materials specifications coexist and both

Box 4.3 Evolution of imperative language standards – GFRP-reinforced concrete

The process for developing consensus for formal standards benefits from the initial development of guidelines. The guidelines serve to accustom the community of stakeholders to the technology. Early adopters develop field experience which supports and helps develop confidence in practices eventually adopted into standards. This is a long process and requires multiple generations of champions to see through as the following example indicates.

The American Concrete Institute (ACI) is the body that promulgates design standards for reinforced concrete in the United States (and is adopted by a number of other countries). The early development of glass-fibre reinforced polymer (GFRP) bars for concrete reinforcement found a "home" at ACI in a purpose-formed Committee 440 *FRP Reinforcement*. In 1996, the first document, ACI 440R-96, was produced. This was a "State-of-the-Art Report" which was essentially a review of literature available at the time. Since FRP was a new technology and ACI is a standards-writing organization, it was critical that this document contain no imperative language ("shall") or recommendations ("should"). In 2001, the first version of ACI 440.1R Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars was published. In order to clearly delineate the nature of this guide, ACI created a new category of document for its publishing: ACI 440.1-01 was an *Emerging Technology* document. An emerging technology document permitted recommendations ("should") but also was required to "identif[y] areas in which information is believed to be less fully developed, and describe research needs." The document was also published with a rather lengthy disclaimer. ACI 440.1R was revised in 2003, still in the *Emerging Technology Series*. In 2006, the third revision was published as a *Guide* without the Emerging Technology tag or disclaimer. GFRP reinforcement was gaining acceptance. A fourth revision was published in 2015. In 2016, ACI Committee 440 began drafting the first design standard for GFRP-reinforced concrete using imperative language ("shall"). This document is anticipated in 2020 – 24 years after the first and almost 30 years after the first ACI "exploratory meeting" was held from which Committee 440 was formed.

drive the other. In the absence of either, the engineer is left wondering where to begin (Box 4.3).

The international bamboo construction community has taken a novel approach to this paradox. The bamboo design standard (ISO 22156) is being redrafted to focus on an allowable strength approach to design (see Box 4.4). Rather than citing test standards or specifications for determining strength, the design standard requires component capacities to be determined by grading consistent with ISO 19624 which sets out guidelines and a protocol for establishing a grading procedure or process.

Box 4.4 Allowable capacity versus allowable stress

Stress is a characteristic of a material whereas capacity (or strength) results from the combination of material properties and *in situ* geometry. Taking the example of a flexural member: the modulus of rupture, f_r, is a stress while the flexural capacity of the cross section of the member is Sf_r, where S is the section modulus – a geometric property. Similarly, the material has a Young's modulus, E, but a flexural stiffness EI, where I is the section moment of inertia.

4.4 Consensus standards development

National and international codes and standards are conventionally 'consensus documents'; that is, they are prepared by a committee of "affected and interested parties" (stakeholders), within which a consensus must be reached. Standards also usually receive public review and all comments received from both the committee and public must be responded to in good faith. An appeals process is also prescribed. Collectively, this is referred to as "due process" and is set out in guiding documents such as *ANSI Essential Requirements* (ANSI, 2018) and ISO/IEC Guide 59:1994 *Code of good practice for standardization* (ISO, 1994). Such due process is the key to ensuring that standards are developed in an environment that is equitable, accessible and responsive to the requirements of various stakeholders and that ultimately they serve and protect the public interest (ANSI, 2018).

Construction standards committees are composed of volunteers. Motivation for serving on such committees varies, but most members – design professionals, producers, academics, government agencies – arrive with an agenda. Indeed, very often stakeholders represent competing interests (Allen, 1992). The consensus process is intended to mitigate competing interests in order to arrive at a standard that best protects the public interest. As a result, consensus standards reflect the state-of-practice rather than the state-of-the-art. Indeed, newly developed consensus standards often reflect 'lowest common denominator' practice and not necessarily best practice. As standards are maintained, they evolve toward best practices. In the case of nonconventional and vernacular materials, mutual relationships between building codes community and regional experts are necessary to ensure sound code development and enforcement processes. This could be facilitated through the engagement of the local building community in a "proactive, constructive partnership with their building code officials" (Eisenberg and Yost, 2004). Such an approach, however, may not convince all stakeholders and a degree of trust and confidence must be established within the standardization process. Essentially, an "expert" is only an expert if accepted as one by their colleagues.

Standards are developed by standard-writing organisations which may take two forms. National (or international) standards organisations (e.g., ASTM, BSI, CEN, ISO, RILEM) whose typical primary objective is founded in supporting interests of national commerce regardless of sector. As a result, the standardization process can become “a political or economical power game although the topics discussed are mostly of a purely technical nature” (Takahashi and Tojo, 1993).

Volunteer standards committees require balance in their membership interest and a critical mass of members is required to take up a new area of standards development. Typically, development of a new standard must find an existing committee to work within which may generate conflicts of interest or gaps in expertize. Entrenched interests and the tendency for “deep pockets [permitting time for review and regular travel to meetings] to dominate the code development process” also affect the progression of codes and standards for nonconventional materials. Examples of this include:

- Structural bamboo standards promulgated by ISO fall within the jurisdiction of the technical committee on timber structures, setting up potential conflicts with those members with links to the commercial timber industry. A Task Group was formed within the committee to promulgate bamboo standards.
- FRP materials intended for concrete reinforcement or repair applications promulgated by ASTM fall within a committee dominated by aerospace interests. In introducing civil engineering infrastructure-related standards into an aerospace committee an expertize gap arose which was addressed by adding additional infrastructure expertize to the committee and eventually establishing a new subcommittee for civil engineering applications.
- The *Australian Earth Building Handbook* was prepared jointly by the Standards Association of Australia, and an external expert. Although the handbook is derived from the work of a Standards Australia Committee, it “should not be taken as representative of the views of committee members” (HB-195-2002).
- ASTM E2392 *Standard Guide for Design of Earthen Wall Building Systems* was created with the intention of developing a technical standard compatible with codes and policies in both the United States and worldwide. Although providing a stepping stone for the representation of earthen construction in globally respected building standards, the document is a “standard guide” using permissive language, rather than code-compliant mandatory language; thus, it cannot be referenced from within building codes (Eisenberg, 2017). Part of the lessons learned in the process of developing this standard are the importance of including a broad array of stakeholders in the process, including private and public sector representation, as well as international experts, researchers, and practitioners. These provided a noticeable representation and a broader perspective when confronting dominating parties in the code writing organisation.

The second type of standards-writing organisations are industry driven and sponsored (e.g., ACI, AISC, fib, etc.). These organisations usually promulgate higher level model codes and benefit from the concentration of expertize that focused professional organisations permit. However, development of standards for new or nonconventional materials will typically not be possible in such focused organisations which may lack the broader expertize and may be in competition with the new material. Nonconventional and vernacular materials are often non-commodified systems that have no ‘industry association’. Often, they cannot be developed into products and cannot be patented. This leads to a lack of financial support and advocacy of nonconventional and vernacular materials at code and standards organisations and committees. Established conventional building materials representation is often compensated by their organization (Eisenberg and Persram, 2009).

In recent years in the United States, an example of a "new" material not having a "home" for standards development arose. Model building codes are promulgated by industry organisations (e.g., ACI 318 by the American Concrete Institute, AISC 360 by the American Institute for Steel Construction, the NDS by the American Wood Council). In the field of pultruded glass fiber reinforced polymer (pGFRP) materials, there was no industry technical organization suited to take on writing a design standard. In this case, a professional organization, the American Society of Civil Engineers (ASCE), stepped in and is drafting a design standard for pGFRP (ASCE, 2010). This was only possible due to ASCE having a sufficiently large membership that an appropriate committee could be formed in accordance with ANSI (2018) requirements.

Most nonconventional and vernacular materials have received little attention in terms of standards development. National standard-writing organisations with limited resources and volunteer committees have little incentive to address technology that is often considered marginal. Where nonconventional and vernacular materials are not marginal, there is little support and often no perceived need for standards. Similarly, there are few established professional organisations who would find nonconventional and vernacular materials in their purview. Ironically: "…*to be able to write a consensus standard, the stakeholder community requires mature practice from which lessons can be learned. To reach this level of practice, standards are required in order to overcome inherent reluctance and cost barriers to adoption of the structural material*" (paraphrased from Mottram, 2017).

One way to overcome this ironic situation is to have existing experts organize in a way that can produce valuable exchange of experience and technical documents. For instance, in the case of the New Zealand earth building standards, the Earth Building Association of New Zealand (EBANZ), with the participation of local engineers and architects, first developed a set of guidelines in 1991. Thereafter, New Zealand Standards (NZSs) took responsibility for the project and joined together with Standard Australia in 1993 to develop a mutual standard with an enlarged committee (Walker and Morris, 1998). The collaboration was discontinued in 1997 mainly due differences in seismic requirements, yet the exchange of information and expertize was valuable. One year later, NZS published the New Zealand earth building standards (NZS 4297; NZS 4298; NZS 4299) which comply with the New Zealand Building Code. Simultaneously, Standards Australia developed *The Australian Earth Building Handbook* (HB-195-2002) and the Earth Building Association of Australia (EBAA) developed the *Building with Earth Bricks and Rammed Earth in Australia* (EBAA, 2004). The hybrid approach of Standards and non-standards bodies' development of construction guidance for earthen material is summarized in Fig. 4.1. The over fifty-year time frame and decades-long development process is of note.

An occasional barrier to this approach is that some nonconventional and vernacular materials enthusiasts resist standards development as a threat to craft-based industry; taking work away from experienced practitioners (Augarde, 2018). This may – mistakenly in the view of the authors – lead to a perceptual coupling between

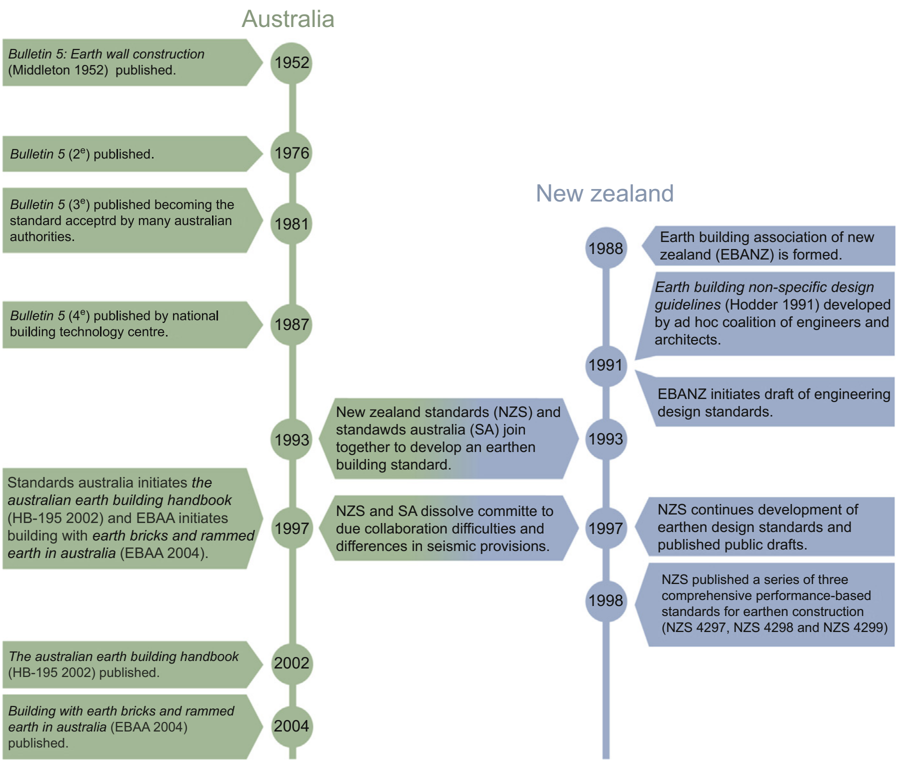

Fig. 4.1 Timeline of New Zealand and Australia Earth Building Standards development process.

sustainable materials and non-standardized materials that are implemented in a bottom-up manner. However, taking such an approach runs counter to establishing sufficient inertia to ensure the acceptance of these sustainable 'alternative materials' into mainstream construction practices.

4.5 "Shall", "should" and "may" — the language of standards

As described previously with respect to ASTM E2392, one result of early standards development is that often initial standards are prepared in non-mandatory language and cannot therefore be adopted by building codes or used for enforcement. Verb form is crucial to standards development. Enacting documents or clauses — those that represent a legal obligation — are conventionally required to provide unequivocal and imperative requirements: "shall". Recommendations ("should") and permissive language ("may") are relegated to non-mandatory appendices or documents because they are unenforceable. Imperative language can also have the effect of focusing the scope of a standard too narrowly, potentially stifling innovation and restricting entry to market of competing or similar technology. When addressing nonconventional and vernacular materials, their variability alone demands the use of more permissive language in many cases. This will favor the development of design guides (or similar) over standards. This dichotomy is seen in the Australia and New Zealand experience described above.

4.6 Types of design standards

Modern building codes are based on a simple 'capacity must exceed demand' approach in which the demand represents the loads applied to the structure and capacity is the ability of the structure to resist these loads. In a more general sense, "performance based design" considers that a structure's performance (defined in a variety of ways) must exceed some minimum requirement – at the very least ensuring the safety of the occupants (the so-called "life-safety" performance level). While most modern building codes are primarily load versus resistance driven, all include some degree of performance requirement as well. Performance requirements are common for aspects of structural behavior that are less quantitative and more qualitative, such as durability and aspects of occupant comfort. The demand and capacity 'sides of the equation' are determined separately – from different standard documents. Load demand on a structure (e.g., ASCE 7, EC 1) is mostly independent of the material from which a structure is built. The load-resistance capacity of a structure is given by material-specific design standards (e.g., ACI 318 and EC 2 for concrete; AISC 360 and EC 3 for steel; NDS and EC 5 for timber). Safety of structural design results from ensuring capacity exceeds demand with a specified reliability. Factors are applied to both the demand (factors greater than 1) and capacity (factors less than 1) sides of the equation; these combine to result in a probability that the capacity will exceed the demand. In modern structural engineering, the probability of failure of a structure subject to its ultimate design loads is targeted to be on the order of 0.0001. The load and capacity resistance factors (alternately referred to as partial safety factors) reflect many aspects of design but primarily represent the uncertainty inherent in making both demand and capacity calculations.

Capacity resistance factors are dominated by the uncertainties associated with material performance. The development of reliability-based partial safety factors or material resistance factors requires significantly more statistical data on material capacity or strength than is usually readily available for nonconventional and vernacular materials. Additionally, the basis for loading and the target reliability index must be known. For this reason, modern load and resistance factor or partial safety design approaches are not generally appropriate for nonconventional and vernacular materials.

4.6.1 Allowable stress approach to design

A simpler method of designing nonconventional and vernacular materials takes an allowable stress approach in which the capacity of a member is limited by its characteristic material strength divided by a 'factor of safety'. Indeed, prior to the 1980s most design codes for conventional engineering materials were based on variations of an allowable stress approach. Most load-determining standards permit or can be adapted for allowable stress design − which considers unfactored (nominal), rather than factored design loads − by simply neglecting the load factors (or using different, reduced factors such as those prescribed by ASCE 7-16). For highly variable materials used in their natural form, such as bamboo, it may be more appropriate to take an allowable member strength approach in which case the load-bearing capacity of the member is the characteristic strength rather than a material strength. This approach, however, leads to more complicated test standard requirements. Whereas standards for establishing a value of stress need only considering fundamental mechanics, component tests involve complex boundary conditions, kinematic and even dynamic considerations. Allowable strength approaches require greater engineering effort and knowledge of the intended final structural use. The latter issue, in particular is, itself, a limit to developing standards.

4.7 'Deemed to comply' alternatives to prescriptive or code-based design

In order to overcome many of the obstacles to standards development for nonconventional and vernacular materials, alternative design methodologies can be promoted as being 'equivalent to' national standards. Similarly, where technological obstacles limit the ability to adopt formal standards, such alternative design methodologies may be 'deemed to comply' with national standards. Such equivalence may be based on experience from previous generations, documented engineering evaluation, or design-by-testing.

4.7.1 Experience from previous generations

Experience from previous generations that is well preserved in local tradition and dutifully transmitted to people living today can be the basis of an informal, non-codified "standard" provided the content and scope are known. This requirement is met when a method of construction or use of material is an "old and pure tradition" or treated as "general wisdom" within a community characterized by a relatively undisturbed social structure having a recognized social pattern. The application of such experience from previous generations is limited to similar scenarios and may not be extrapolated in terms of dimensional scale. Experience from previous generations is not transferable following migration (ISO 22156).

4.7.2 Documented engineering evaluation

Reports based on evaluations, such as those commonly made following natural disasters, documenting construction methods and structural designs that demonstrably satisfied design requirements may be equivalent to standards under similar scenarios.

Such reports should be prepared by acknowledged design professionals and be accepted by the national or international technical community following appropriate peer review. The application of documented engineering evaluation is limited to only scenarios similar to those documented and should not be extrapolated in terms of dimensional scale. An example of such documentation is inclusion in the World Housing Encyclopedia (WHE).

4.7.3 Design-by-testing

Many building codes permit variations on ‘design-by-testing’ (see Box 4.5). Typically used when the composition or configuration of structural members or systems are such that design by code provisions is not possible, testing prototype systems provides a means of assessing structural performance in terms of the intent of the Code. Tested prototypes must be structural assemblages including members and connections, isolated by definable and reproducible boundary conditions (an example is that joint region tests should include members sufficiently long to be supported at their expected locations of contraflexure). It is good practice to conduct a peer-review of the test protocol prior to testing in order to ensure that the desired behavior is being modeled in the test. Prototype tests should be conducted at full-scale, use the same materials as the intended structures, include replicate specimens and be overseen by a design professional. Such tests are not ‘proof tests’ and must be carried to failure with failure modes reported. Tests should be reported in a manner suitable for peer-review and the report should provide sufficient detail that the testing could be repeated.

4.8 Appropriate codes and standards for nonconventional and vernacular materials

Angelino et al. (2014) propose a framework for defining and measuring the quality of codes and standards in the construction industry. A primary hypothesis of Angelino

Box 4.5 Design by testing for timber structures

Because of the considerable variation possible, design by testing practices have been largely standardized for timber connections. Using International Standards as an example: ISO 16670 *Timber Structures — Joints made with mechanical fasteners — Quasi-static reversed cyclic test method* prescribes a series of rigorous testing protocols. ISO TR 21141 Timber structures - Timber connections and assemblages - Yield and ultimate characteristics and ductility from test data prescribes uniform interpretation of resulting test data to obtain design values: yield and ultimate capacity, joint stiffness (or slip) and ductility. Finally, ISO 12122-5 *Timber Structures — Determination of Characteristic values — Part 5: Connections* prescribes the method of establishing characteristic design values based on replicate test data.

et al. is that reducing complexity improves quality of codes and standards. First, the "purpose" of the code or standard must be identified and this should guide the drafting of the document at all stages. The purpose of a design standard is different from different stakeholders resulting in varied interpretations of the standard. Using the framework proposed by Angelino et al. (2014) as an inspiration, the objectives of design standards for nonconventional and vernacular materials should consider the following features:

- be viewed as a system to codify existing or vernacular or traditional knowledge; and
- provide a concise system of provisions for nonconventional and vernacular building systems that were not previously inspected or regulated.

Standards should include a system to:

- guarantee structural safety;
- design structures that are environmentally, socioculturally, and economically sustainable;
- aid common design situations while supporting innovative design; and
- build a common and shared design language.

While all valid, depending on context, some objectives might be more relevant than others. Ultimately, a general statement of purpose for a design standard for nonconventional and vernacular materials may combine two or more of the above features. A very specific mission statement is included in the New Zealand Earth Building Standards: "The objective of this Standard is to provide for the structural and durability design of earth buildings. The Standard is intended to be approved as a means of compliance with clauses B1 and B2 of the New Zealand Building Code" (NZS 4297). A more general example may be to codify existing knowledge in order to ensure structural safety, as well as to address common design situations while providing means of compliance with building codes and supporting innovative design.

"Usability" of a standard, as the word implies, must be based on the needs and expectations of the user. De Weck et al. (2011) describes usability as being founded on how users perceive the quality of the standard in addition to the impact of unanticipated difficulties (in terms of time and effort) arising from its use. Angelino et al. (2014) identify the following attributes (a subset of a series of keywords referred to as "quality dimensions") that inform the "ease-of-use" of a design standard:

- *accessibility* – the extent to which provisions are easily and quickly identified within the standard;
- *clarity* – the extent to which provisions are clear in scope, including limitations;
- *coherence* – the extent to which provisions are presented in a logical manner;
- *completeness* – the extent to which provisions are sufficient for the design required;
- *conciseness* – the extent to which provisions are written in a succinct manner;
- *ease of navigation* – the extent to which provisions are connected and the links are easy to follow;
- *simplicity* – the extent to which provisions may be applied by users without understanding all of the underlying principles;
- *understandability* – the extent to which provisions are easily comprehended by the target users, minimizing the risk of misinterpretation.

Demonstration of ease-of-use may be through development of representative examples. These are typically published as a non-mandatory companion to a standard document. Examples, however, are a double-edged sword: while improving *simplicity* and *understandability*, their blind application by those with inappropriate expertize may be dangerous. Benchmarking by example may also unintentionally stifle innovation when a new concept does not “fit the example”.

An alternative to presenting examples is to develop navigation flow charts for design standard provisions or typical design cases (an example of this approach is used in AASHTO, 2017). These serve to improve *ease of navigation* but are also a tool the standard authors can use to ensure *clarity* and *completeness*. Development of a design work flow chart can identify provisions which are incomplete, lead to ‘dead ends’, or result in complex iterative procedures.

4.9 Challenges and opportunities of codes and standards development for nonconventional and vernacular materials

Codes and standards development has been described as “a long and onerous” process (Mottram, 2017). Particularly for materials having no existing precedent, the task is daunting and meets resistance at many steps. The following enumerates many of the challenges and possible strategies to overcome these issues.

Finding the Motivation for Standards Development **-** First and foremost, a need or motivation is required in order to promote the development of standards for nonconventional and vernacular materials. The primary driving motivation of building codes today is public safety and general welfare. The vision of the International Code Council is to “protect the health, safety and welfare of people by creating safe buildings and communities” (ICC, 2018). In addition to life safety, there is a growing awareness to the importance of environmental sustainability that catalyses the standardization of these materials (Eisenberg and Persram, 2009). Nonconventional and vernacular materials often offer an ecologically-based solution, ensuring that long term public safety, health and welfare are retained. In addition, factors such as changing environment (e.g., climate change and sea-level rise), changing demographics (e.g., urban migration), and changing industry needs are also important.

Establishing a Collaborative Standardization Framework - As has been described, standards development must take place within an existing framework. This framework may not have the technical expertize or commercial motivation necessary to commit to a standard-development process. Therefore, in order to initiate the process for nonconventional and vernacular materials, collaboration is often required between associations representing technical expertize and governmental organisations to provide an adequate financial and motivational framework (this has been proven successful in the case of the New Zealand Earth Construction Standards).

Including a Broad Stakeholder Community - Standards development should involve all stakeholders, but engagement in the process is usually voluntary. This results in a degree of self-selection in terms of the stakeholders' involvement and requires that stakeholders have the necessary resources available to voluntarily engage in the process. This resource availability is particularly difficult to ensure when considering nonconventional materials having an international scope. Such development often takes place at the hands of a few "champions" rather than the broader stakeholder community.

Developing a Sound 'Engineering Judgment' - Assimilating the engineering data, expertize, and knowledge often takes years to achieve and is critical to the standards-development process. For this reason, standard development for nonconventional and vernacular materials must begin with synthesis of the existing engineering data, as well as documentation and enhancement of local practices. As mentioned previously – codes and standards reflect state-of-practice rather than the state-of-the-art. This is an iterative process of continuous improvement (so-called "maintenance") of standards worldwide.

Proper Documentation and Analysis of Test Studies **-** Although most nonconventional and vernacular materials have a long history, it is typically *ad hoc*, anecdotal and not suited to developing standards. For instance, there is often a lack of fundamental statistical data on material properties; this is a significant barrier to integration of these materials into the framework of most modern design standards. Thus, in order to contribute to the body of literature and to future standardization, nonconventional and vernacular materials test studies should include proper documentation and analysis of their results including the reporting of metadata (means and methods, etc.). Reported test results should include properties of constituent materials (when applicable), and should clearly present statistical evaluation. Source data must also be readily available – this is well supported by a variety of digital archives including universities, thesis repositories and peer-reviewed journals.

Even where data exists in the technical literature, it is often inconsistent in what data is actually reported and typically does not include important metadata. Common weaknesses with published research relevant to informing the preparation of design rules (Mottram, 2017) must be overcome as follows; study authors should:

- provide clear definition of the domain of applicability of the work.
- provide critical review of previous research relevant to that domain.
- ensure that all crucial data on properties of specimens is reported. For instance, the authors have seen papers reporting the properties of bamboo that fail to report species!
- adopt test methods that describe capacities or properties relevant to design and/or describe the engineering significance of the data reported.
- consider practical aspects, such as the construction methods applied on site, as well as the effects of imperfections that occur in practice.

The importance of the latter two items is demonstrated in studies of earthen construction (Ben-Alon et al., 2017). Some researchers are able to use field-made specimens while others fabricate specimens in the laboratory, potentially resulting in a bias in terms of production quality. Furthermore, researchers have adopted different established test methods – some for concrete materials, others for masonry units, and even others for masonry assemblies – and their attendant specimen geometries.

These result in a considerable range of reported data that cannot be directly compared. In some cases, test method selection results in an extreme bias in reported properties. For example, Ben-Alon et al. reports that different studies report the modulus of elasticity for compression of cob material to vary by an order of magnitude depending on the test method used.

Homogenization to Mitigate Material Variability - Nonconventional and vernacular materials are not uniform from environment to environment, further complicating the process of 'assigning numeric values' that typify the standard-development process. Therefore, similar to what is done in timber codes and standards, a homogenization approach grouping different species or 'classes' of materials is appropriate for nonconventional and vernacular materials.

Conducting Missing Research - There are currently large gaps in the knowledge of nonconventional and vernacular materials that should be addressed in order to allow regulatory justification and standards development for these materials. In particular – there is limited formalized scientific data on long-term durability and thermal performance in different climatic contexts. In terms of structural data, the ability of connections to transmit loads, as well as the seismic performance of building elements should be further studied. These research areas require significant resources and time for study.

Avoiding Unnecessary Complexity in Standards - Angelino et al. (2014) argue that modern engineering design standards have reached a level of complexity that impacts negatively upon both their quality and ease of use. The authors argue that such complexity increases the risk of misinterpretation of the code or standard. When considering nonconventional and vernacular materials, the user community may be further removed from the standards development process increasing the risk of misinterpretation. Indeed, the present authors contend that unnecessarily complex standards in the field of nonconventional and vernacular materials may lead to the standards simply not being applied at all. On one hand, the opportunity afforded by nonconventional and vernacular materials for starting with a "blank page" when developing standards should be used to mitigate unnecessary complexity. On the other hand, existing codes and standards as well as committee constitutions that prove successful should be used as exemplars to avoid excessive complexity that results from "re-inventing the wheel". The reality will lie somewhere in the middle: leveraging existing codes and standards while reducing the complexity in accordance with the reduced degree of certainty we anticipate in terms of fundamental material properties.

4.10 Conclusions, observations and needs for the future

Building Codes, Design Standards and Materials Test Standards and Specifications for nonconventional and vernacular materials will, necessarily, take a different form than those for engineered materials. Standards written in mandatory language ("shall", rather than "should" or "may") are a stage in the evolution of acceptance of a material or technology demonstrating maturity. Prior to this, non-mandatory guide documents help to acclimatize the engineering and stakeholder communities to the materials and provide a basis for early-adopters — helping to establish a critical mass and motivation for standards development. This process is multi-generational; thus the guidance documents also help to provide the necessary continuity. Importantly, champions and early-adopters of nonconventional and vernacular materials should not be discouraged by the lack of mandatory standards — it is an indication that they are ahead of the curve.

Development must not occur in a vacuum. Many of the likely benefits of nonconventional and vernacular materials reside, not in their structural performance, but in (for example) their thermal, sustainability, social, and aesthetic performance. It is these benefits that will provide the motivation for the standards development process and may well introduce non-traditional stakeholders into the process. While nonconventional and vernacular materials are mainly developed in a bottom-up approach by advocates with little funding, it is crucial that collaborations take place between entities (e.g., governmental and regulatory organizations), and practitioners (e.g., researchers and field experts). Potential barriers that must be overcome include the lack of aggregated and properly documented engineering data, especially in the fields of durability and fire resistance, as well as a lack of experience in the standards development processes among experts in these materials. In this context, existing guides and examples that are proven successful should be used to mitigate excessive complexity as well as to provide useful design parameters. Ultimately, resources should be made available for research and education, as these are a key to increasing awareness of the advantages of non-conventional and vernacular materials and consequently to their formalization in codes and standards. In this context, the environmental and societal needs for nonconventional and vernacular materials can be evaluated, as discussed in Chapter 3 of the present book, and should be addressed by policy makers through their endeavors to catalyze the development of nonconventional and vernacular codes and standards.

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