Structures 3 (2015) 227–235

Contents lists available at ScienceDirect

Structures

journal homepage: http://www.elsevier.com/locate/structures

Timber gridshells: Numerical simulation, design and construction of a full scale structure

B. D'Amico [a,*], A. Kermani [a], H. Zhang [a], A. Pugnale [b], S. Colabella [c], S. Pone [c]

[a] School of Engineering and the Built Environment, Edinburgh Napier University, Edinburgh, UK
[b] Faculty of Architecture, Building and Planning, University of Melbourne, Melbourne, Australia
[c] Department of Architecture, University of Naples Federico II, Naples, Italy

ARTICLE INFO

Article history:
Received 18 February 2015
Received in revised form 6 May 2015
Accepted 17 May 2015
Available online 2 June 2015

Keywords:
Gridshell
Active-bending
Timber
Dynamic Relaxation
Computational form-finding

ABSTRACT

Timber gridshell structures, such as the Multihalle for the federal garden festival in Mannheim or the Downland Museum, have been the result of a creative–generative process that indissolubly 'welded' the structural contribution to that of form exploration. The challenging design and construction issues have been typically addressed and resolved in several inventive ways. However, still now, form-finding and erection of timber gridshells present many difficulties. In this regard, this paper aims to provide a series of novel steps to address some of the main design and construction issues that are associated with 'actively-bent' timber gridshell structures. First, the main characteristics of the construction process of timber gridshells are described and the basic theoretical concepts for its numerical simulation, through Dynamic Relaxation method, are introduced. Second, a practical method for sizing the laths' cross-section is presented. Third, a new erection technique for timber gridshells is proposed and applied to the construction of a full scale (prototype) structure, the Toledo gridshell 2.0. Fourth, a new bracing system for the same structure, which was built at the Faculty of Architecture, University of Naples Federico II in June–July 2014, is explained and discussed. The paper also highlights the need for further application to validate the techniques explained here, with particular attention being paid for the construction of large scale free-form structures.

© 2015 The Institution of Structural Engineers. Published by Elsevier Ltd. All rights reserved.

1. Issues of post-formed timber gridshells

The term 'active-bending' refers to those structural systems in which a curved geometry is obtained through bending of elastic elements. It does not define a structural typology in itself. Rather, it groups different design approaches of constructing through bending. A detailed categorization is provided in [1] where a synoptic table relates forms and geometries to such approaches. In this paper, focus is only given to the particular construction system of gridshells — pre-assembled flat quadrilateral grids of straight and continuous elastic rods, which are subsequently post-formed, that is to say bent, into doubly-curved form-resistant shells (see, for instance, Trio gridshell in Fig. 1). In fact, the doubly-curved — initially flat — gridshell, undergoes *extentional* (in-plane) deformations as a combination of the rods' bending and shear deformation of the initially square quadrilaterals. Such a 'pantograph kinematics' is prevented to occur at completion of the erection process by diagonal bracing systems, triangulating the quadrangular grid geometry. A review of relevant post-formed gridshell projects can be found in [2]. The described construction method generates structural forms by using standardised connection systems, such as single-bolts [3,4] or clamping plates and devices [5,6]. However, such a repeatable and feasible solution has still to deal with the definition of the gridshell form, as well as with the design of an erection technique to bend the starting shape. This means that both theoretical and practical issues can only be addressed through a preliminary form-finding procedure and simulation of the erection, or forming, process.

In addition to this, the assessment of a 'feasible' size for the cross-section of bending members has to be performed. For instance, for a bent rod made of an elastic material with a given modulus of elasticity and strength, we have that the higher the curvature to be reached, the lower the allowed thickness of the rod will be. However, such a thickness might not be sufficient to provide the necessary structural performance. In the design of the Mannheim timber gridshell for the federal garden festival [3] this issue was brilliantly overcame with a double-layer system of overlapping timber laths. Compared to a single-layer system with equivalent cross-sectional area, this solution allowed for tighter curvatures to be reached. Thus, at completion of the bending process, the sliding between overlapping laths was restrained hence greatly increasing the bending stiffness of the built-up member. Regardless of the number of layers, the allowable cross-section, still needs to be

---

* Corresponding author. Tel.: +44 131 455 2249.
E-mail addresses: bernardinodamico@gmail.com, b.d'amico@napier.ac.uk (B. D'Amico), a.kermani@napier.ac.uk (A. Kermani), j.zhang@napier.ac.uk (H. Zhang), alberto.pugnale@unimelb.edu.au (A. Pugnale), sofiacolabella@gmail.com (S. Colabella), sergio.pone@unina.it (S. Pone).

http://dx.doi.org/10.1016/j.istruc.2015.05.002
2352-0124/© 2015 The Institution of Structural Engineers. Published by Elsevier Ltd. All rights reserved.

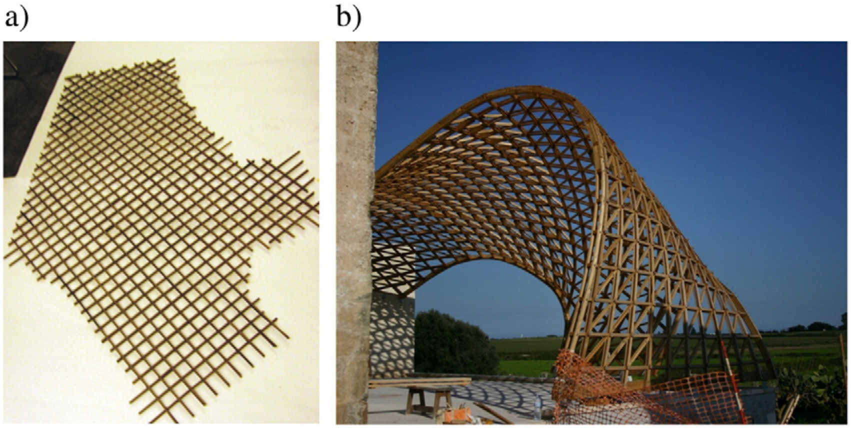

Fig. 1. Trio gridshell in Lecce, Italy 2010 (CMMKM Architettura e Design): (a) Scale model of the flat grid; (b) post-formed grid with diagonals bracing.

assessed for each and every single lath, especially at early/conceptual design of the structural form.

2. A theoretical model

The form of actively-bent structural systems cannot be chosen a priori. Rather, it will have to comply with the equilibrium of external (shaping) forces and internal reactions due to material and geometric stiffnesses. Accordingly, as for other kind of lightweight systems, as for instance tension structures [7] or reciprocal structures [8] some sort of preliminary form finding procedure is required.

Assuming, in first instance, the seeking of the post-formed gridshell geometry as a simulation of the construction process by means of Finite Element (FE) procedures, thus representing the geometry as a finite set **P** of nodes having nodal coordinates $\overline{p}_i$ in the Cartesian space:

$$\mathbf{P} = \{\overline{p}_1 \ldots \overline{p}_i \ldots \overline{p}_m\} \quad ; \quad \overline{p}_i = [x \;\; y \;\; z] \qquad 1$$

and a connectivity list **E** storing the node's indexes of the *j*th beam-element's end nodes (1,2):

$$\mathbf{E} = \{\mathbf{e}_1 \ldots \mathbf{e}_j \ldots \mathbf{e}_n\} \quad ; \quad \mathbf{e}_j = \{i_1, i_2\} \qquad 2$$

then, the form finding problem is reduced to solve the following system of equations:

$$\mathbf{K}\boldsymbol{x} = \boldsymbol{f} \qquad 3$$

where the vector of nodal displacements $\boldsymbol{x}$ from the unstressed initial position, corresponding, in our case, to the flat mat geometry, is obtained as a function of the system stiffness matrix **K** and the vector of applied nodal forces $\boldsymbol{f}$ shaping the grid:

$$\boldsymbol{x} = \mathbf{K}^{-1}\boldsymbol{f}. \qquad 4$$

In the 'general' case of small displacements theory, a linear relation is assumed between the displacement vector $\boldsymbol{x}$ and the load vector $\boldsymbol{f}$ and the problem is complied by computing the matrix **K** (Direct Stiffness Method [9]) according to the initial unstressed geometry. Such an approach is clearly unacceptable to simulate the large displacements involved in the forming process of elastic gridshells. Therefore, an iterative technique is required. The 'dominant' method in structural engineering for solving the system of non-linear equation (Eq. (3)) is known as the Transient Stiffness Method (TSM). As noted by Lewis [7] the method '...*evolved from the conventional, small displacement theory*', in that of keeping a linear relation between the vector of nodal forces and corresponding nodal displacements. However, unlike in the small displacements theory, the vector load is applied incrementally so that, the linearised displacements are 'corrected' and the stiffness matrix 'updated' at each increment (Full Newton–Raphson) in order to minimize the residual error (vector of out-of-balance forces) occurring as a consequence of the linearisation. Applications of the TSM for the form finding of post-formed timber gridshells (by means of Abaqus commercial software) are reported in [10,11] (see Fig. 1). In these, the simulation of the forming process allowed to find the gridshell geometry as well as assessing the resulting bending stress field, to be used as basis for the dimensioning of cross-section of the laths.

Clearly, a simulation of the forming process requires to know in advance the cutting pattern of the flat mat, corresponding to the initial unstressed geometry, as well as a vector of the external applied forces (or imposed displacements) needing to shape the mat according to the desired doubly curved shape we are looking for. For instance, according to Harris et al. [5] to design the Downland gridshell, physical scale modelling was used to determine the vector of boundary conditions for the form finding model, while the flat mat was (a priori) established to have a rectangular contour perimeter (cutting pattern). Without doubt, a form finding procedure allowing to find the grid cutting pattern as well (according to a desired final shape) would be preferable to a 'mere' simulation of the construction process. An effort to define a 'comprehensive' approach to the form finding of post-formed gridshells can be found in [12–17]. In these, the main highlight is the use of a reference surface (acting basically as a form-work) on which 'forcing' the elastic grid to be deformed. Then, in a second analysis step, the grid geometry exceeding the reference surface is removed from the analysis (a cutting pattern is so found) as well as the reference surface, thus, boundary constrains are added to the system and, at equilibrium convergence, the system settles down in its final static equilibrium. Clearly, in order to perform the described method, the initial mat geometry (node list **P**) will have to lie on the reference surface, meaning that, unlike for a mere simulation of the forming process (where initial and unstressed geometries are coinciding) the initial geometry, at the start of the non-linear analysis will likely be far enough from static equilibrium to be intractable by TSM schemes (lack of numerical convergence). Accordingly, an explicit Finite Element procedure, such as the Dynamic Relaxation (DR) may be more suitable to be implemented in form finding frameworks expecting the use of a reference surface.

2.1. Dynamic Relaxation method: basic concepts

The DR is an iterative time-stepping marching scheme, according to which, the original system of non-linear equation (Eq. (3)) is transformed into a system of equations of motion by introducing lumped nodal masses and viscous damping forces [18] needed to allow the system reaching a rest configuration:

$$\mathbf{M}\boldsymbol{a} + \mathbf{C}\boldsymbol{v} + \mathbf{K}\boldsymbol{x} = \boldsymbol{f} \qquad 5$$

Download English Version:

https://daneshyari.com/en/article/6774765

Download Persian Version:

https://daneshyari.com/article/6774765

Daneshyari.com