448: Efficient structural roof form as a tool for energy savings in building design

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Abstract

Opportunities for increasing energy-efficiency in the built environment may be found by dividing the energy consumed by buildings into three life-cycle phases: the Pre-use phase (embodied energy), Use phase (operational energy), and Post-use phase (demolition, re-use, or recycling). Today it is well known that as operational energy use is reduced, the relative importance of embodied energy becomes more apparent. Within the initial embodied energy of a building, the structural system can be the major component. Currently, reinforced concrete frame technologies constitute a standard structural system commonly employed in low-rise buildings.. This ongoing study, conducted in a seismically active desert region, examines the potential life-cycle energy savings that may be achieved by the exploitation of alternative structural roof forms, which by carrying their loads efficiently may greatly reduce the reliance on cement and reinforcing steel, both of which contribute to the high energy-intensity of typical building structures. A complex energy-based optimization framework is proposed, using computational tools for design, analysis and prediction. The objective is to minimize the use of high-embodied-energy building materials and their effect on the whole life-cycle energy consumption, while satisfying mandatory national building code performance requirements for structural reliability and serviceability. The analysis of optional designs takes into consideration the particular characteristics of the local area – such as climatic considerations, transportation distances, seismic risk, etc. Hence, the optimization method proposed integrates a number of techniques: a form-finding process which includes structural analysis, a thermal simulation, and a life-cycle energy assessment (LCEA) evaluation over a 50-year life span. The method may serve as a decision support means from the early schematic phases of environmentally-responsible building design.

Keywords: Life-cycle energy assessment, embodied energy, optimization, structural system.

1. Introduction

In industrialized societies, buildings account for a large fraction of the overall energy consumption: residential and commercial buildings are responsible for approximately 40% of the total [1, 2]. These sectors, however, only account for the energy consumed in buildings during the period of their active usage. The share of energy used by buildings increases significantly when the energy used in their production and demolition is included as well.

Any comprehensive assessment of the total energy consumed by buildings must in fact consider the entire life cycle of the building, which can be divided into three phases: *Pre-use phase* (embodied energy - EE), *Use phase* (operational energy - OE) and *Post-use phase* (demolition or possible recycling and reuse).

Some studies have indicated that the initial energy needed for production of a building is minor compared to its long-term operational needs. It is clear, however, that as advances are achieved in the thermal efficiency of building envelopes and systems, the role of embodied energy in minimizing overall consumption becomes increasingly prominent [3]. In fact, some of these technological innovations are in themselves predicated on high EE materials (e.g. metals, glass and plastics) and processes (advanced window coatings, etc.).

Depending on the expected lifetime of the building and its operational energy efficiency, the pre-use energy typically represents between 10% and 60% of the total energy used during the life time of the building [4]. Within this total embodied energy, a building's external structure and envelope (roof, floor, walls and windows) tend to account for the greatest portion [5].

Conventional reinforced concrete structural systems have been identified as a major consumer of embodied energy in buildings. The high energy intensity of these frame structures is closely related to the *geometry* of their horizontal spanning elements, whose bending stresses impose especially large requirements for reinforcing steel.

It was found in a previous study [6] that the embodied energy of a climatically-responsive residential building in the arid Negev region of Israel, assuming a life span of 50 years, may account for as much as 60% of its overall life-cycle energy consumption, and about two thirds of this (i.e. 40% of the total) may be attributed to its reinforced concrete structure [4]. These findings indicate the importance of energy-efficient ***structural systems*** within the overall challenge of sustainable resource-use in the built environment.

2. Energy in standard structural systems

The emergence of new materials has masked the necessity for efficient structural form, since their strength compensates for higher internal stresses. The use of frame skeletons, exploiting dimensioned lumber, steel or reinforced concrete (RC), is typical for low-rise buildings in developed countries and represents an easy and rapid solution for high-volume building construction. Almost all the structural components resist forces by bending, and this dictates the use of materials which are high in tensile strength – and usually in embodied energy as well.

The steel sector is one of the most energy intensive end-use sectors, and is responsible for over 5% of all global anthropogenic greenhouse gas emissions [7]. The EE of steel is approximately 35 MJ per kilogram – which, at a typical density of 8,000 kg/m^3, amounts to some 280,000 MJ per cubic meter [8]. When deployed as reinforcing in structural concrete, its EE contribution may be as high as 1500 MJ/m^2 of building area [4]. The problem generated by excessive steel use in terms of energy as well as its obvious long-term economic cost was already predicted by Alexander in the 1970's [9].

In addition to the high embodied energy values of reinforcing steel, concrete's environmental impacts are mostly related to the production of cement, a notorious source of CO_2 emissions. EE values of non-reinforced concrete are in the range of 2070-4180MJ/m^3 [4].

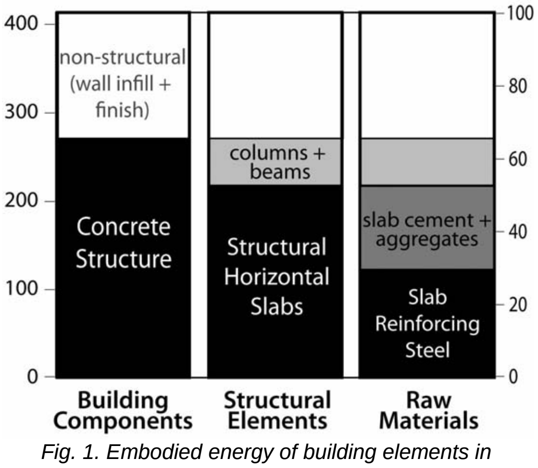

Fig. 1. Embodied energy of building elements in conventional concrete construction, shown in GJ (left axis), and in % of total (right axis). Adapted from [6].

In standard RC frame construction the floor, ceiling and roof elements consist of horizontal planar slabs. As calculated from a previous study, RC horizontal slabs may represent over 50% of the total EE of the structure, and the largest portion of this (about 30% of the total) is accounted for by reinforcing steel [6].

Another study estimates that the source of about 60% of the environmental load of building materials used for offices is the supporting structure, and within the whole bearing structure, the horizontal structural elements (floor, roof and beams) are responsible for 80% of the environmental loads [10].

The need for reducing the amount of materials (for economic purposes and in turn for environmental ones) has been translated into a search for lightweight structures. The use of reinforced concrete allowed thinner structures than masonry compression-only curved forms used in the past, a trend which may potentially save resources. At the same time, however, higher quantities of tension-resistant materials are required, particularly steel – which, as mentioned above, is also highly energy intensive. In addition, lightweight tension-only structures are difficult to design and build, often provide poor thermal characteristics, and require a great quantity of steel, which may be difficult to justify for all but the largest wide-span public buildings, such as stadiums.

Likewise, the structural form of the envelope can significantly influence the thermal behaviour of the whole building. The roof in particular can have a considerable influence on the thermal performance of buildings since its surface is oriented towards the sky and hence it is the area most exposed to intense energy exchange by incoming radiation during the day and out-flow at night [11]. It was found that in an arid area, the roof is responsible for 50% of the building's total heat load [12].

Therefore, the form of the roof is extremely important as it is responsible for the level of exposure to the external environmental conditions. Compared with a horizontal planar roof, domes and vaults may absorb significantly less net energy [13], and non-planar roof forms allow possibilities for improving thermal comfort through indoor air stratification [14].

3. Efficient structural roof forms

Structural efficiency is generally associated with material saving requirements. Efficient structures accomplish this objective by transmitting forces as directly as possible – with a minimum number of elements, minimum material, and maximum safety.

Greater material efficiency may be achieved in such structural elements by minimizing *bending* behaviour, which generates uneven stresses. In this sense, the most efficient structural type is a *form-active* structure, which, as classified by Engel [15], is a structure or structural element that transmits loads through axial forces only, with constant stresses over its cross section. In this way, the material provides full structural value for its weight. Alexander [9] adds that an efficient structure should also “act as a whole” – meaning that it is *continuous*. This continuity is expressed in terms of the material used as well as the shape of the connections between elements, and as such this principle of continuity also relates to the *geometry* of the overall structure.

Hence, structural efficiency depends on system and element level geometry, in addition to the material strength and stiffness properties. Two basic structural forms meet these conditions for an efficient structure in which bending is avoided [9]: pure tension structures (e.g. tensile membranes and cables), and pure compression structures (e.g. arches and vaults). In these cases the shape of the longitudinal axis, in relation to the pattern of applied load, is such that the internal force is axial and the structure is stressed to its maximum allowable limit, operating at its full capacity.

Efficient structural forms, then, rely on the geometry of the whole and the size of the parts to work together in giving the greatest strength with the least material – yielding stable, and often elegant, structures. Structures that are resistant by form tend to embody an intrinsic relationship between forces and physical shape: “structural clarity”, which calls for design methods that may differ from those to which architects have become accustomed.

The study of the relationship between structural form and force can be traced to the 17th century, with the understanding of the catenary (*Fig. 2*). As the inverse of the "hanging chain," the catenary arch relies on an "ideal" geometry for achieving uniform axial compressive forces.

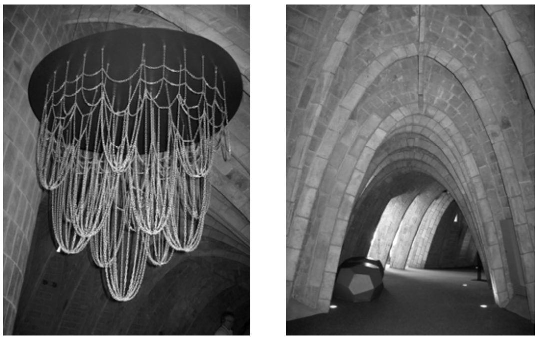

Fig. 2. Examples of catenaries in Gaudi’s work

Arithmetical or geometrical rules for structural design were employed until the nineteenth century, when masonry architecture began an accelerated decay, due to the appearance of new materials (iron, steel, reinforced concrete) and new structural types (frames, trusses, thin shells). As the range of technologies available became wider, the importance of the geometrical configuration in determining structural actions was reduced.

While maximum structural efficiency is an ideal to be strived for, external non-structural constraints may sometimes lead necessarily to a selection of less efficient structures. Such an example can be found when minimization of total cost is the principal objective. Initial monetary costs, energy costs and structural efficiency are not necessarily correlated in a simple way: an improvement in structural efficiency as typically defined does not ensure reductions in energy consumption.

4. Existing knowledge

Building designers and researchers have long searched for structural solutions that provide geometric freedom while achieving economic efficiency through the efficient transfer of loads and the reduction of material weight. They look for structures whose curvature transfers stresses more efficiently with little to no bending moments, making them stiffer than conventional flat surfaces. Yet, the problem of energy efficiency has not often been included in this search.

A number of studies have analyzed the embodied energy invested in buildings which use the three most common structural technologies: concrete, steel and wood [16]. They have identified the most energy-intensive factors within each structural types, and possible improvements that can be achieved through judicious changes.

Some strategies are informed by vernacular approaches that have been largely discarded, reviving traditional materials such as adobe and rammed earth. These traditional materials are in some cases combined with new techniques, including the use of efficient forms to improve mechanical behaviour. The EE of industrial and natural materials has been compared, and new computer design tools have been developed to analyze historic masonry methods [17].

New movements have appeared in a number of disciplines that search for efficient design practices by observing and taking examples from nature. These approaches identify the natural process of evolution as inherently efficient in relating function, form and use of resources. Such “evolutionary optimization techniques” have been developed in computer science, as analytical tools which can be used for applying these principles in practice.

Optimization as a tool for improving energy efficiency in buildings has recently begun to be used for *operational* energy savings, mostly with genetic algorithms, but is still in development [18]. Pushkar et al. [19], have included production, operation and maintenance in a proposed methodology for environmental optimization of buildings in the design stage. A study on environmentally based optimization of cross-sections of horizontal reinforced concrete slabs by using recycled or waste products has been presented [20], though the form of the slab as a whole was not optimized.

Alexander [9] proposed the use of vaults as an advantageous roof form for achieving efficient structures, and he extensively studied the utilization of lightweight concrete for ceiling and roof vaults with minimal bending stresses. Minke [21] presented constructional details and coordinates for structurally optimized domes of different proportions, and recommendations for safer vault construction for earthquake-resistant houses built of earth. The use of curved forms for achieving better structural performance when employing newly developed materials such as FRP has recently been initiated [22], though not with the aim of reducing environmental impacts. The possibility for reducing embodied energy by designing efficient structural forms has in fact been recognized, but mainly for long-span buildings (and especially lightweight structures), as applied in a few examples in practice [23].

However, none of these quantified actual EE (or life-cycle energy) values, or offered general recommendations for future application. The evaluation of the effects of efficient forms on the life-cycle energy consumption of buildings as a whole is a time consuming process and requires tools from a number of disciplines, and perhaps for this reason has not been applied for small low-rise projects.

Therefore, this study aims to present a framework for identifying energy efficient structural roof forms that may decrease the whole-life energy expenses of typical low-rise buildings, while maintaining their structural integrity.

5. Proposed Method

The proposed method, hence, aims to examine how the “strength through shape" principle can ultimately be employed to improve the energy efficiency of common buildings that are produced on a large scale. In particular, it will enquire whether curved roof forms such as vaults (that are more structurally “efficient” than equivalent rectilinear forms) may be employed practically as an energy efficient tool to reduce whole life cycle energy consumption in buildings - particularly in desert areas (where local sources of timber are scarce) that seismically active (thus requiring ductility as well as load-bearing capacity in structures). The premise underlying this is that significant potential energy savings and reductions in the exploitation of natural resources lie in diminishing the embodied-energy of buildings by means of alternative non-planar and efficient structural forms.

For that reason, this study assembles the required simulation tools (structural and thermal) in an integral optimization process, to evaluate the potential of efficient structural form for minimizing the life cycle energy consumed by low-rise buildings in arid and seismic regions. The ultimate output of the proposed methodology is a set of alternative structural roof forms that meet the region-specific needs/demands for buildings, while at the same time reduce the use of highly energy-intensive manufactured materials.

The study is focused on alternatives to conventional concrete-slab construction, which is common for low-rise residential buildings in Israel and many other countries. The identification of structural configurations with minimal cumulative energy consumption is done using Life-Cycle Energy Assessment (LCEA) methods [24], focusing on principal energy flows during the pre-use and use phases of the building’s life cycle (neglecting post-use energy consumption for demolition and disposal).

To allow for comparisons between alternative scenarios, a multi-faceted *optimization framework* is proposed that includes simulation analyses to evaluate system performance and iterations in order to weigh the effects of changes. These optimization techniques allow for relatively quick and easy estimation of a large number of options. Energy cost savings are stated relative to a base case model. The study region (Sede-Boqer, in the arid and seismically active Negev region of southern Israel) is selected for the purpose of obtaining appropriate climatic and seismic data, as well as for calculating or selecting site dependent values such as EE coefficients of materials.

Given that the structural component that represents higher embodied energy consumption values is the slab, diverse roof form options are analyzed and proposed (*Fig. 3*), while a standard RC bearing structural column-beam skeleton is the common supporting structure for all the alternatives, based on common practice in the area. Two general roof typologies can be analyzed with the proposed methodology: form-active (compression-only) structures – principally vaults, and surface-active systems (in-plane stresses) – shells.

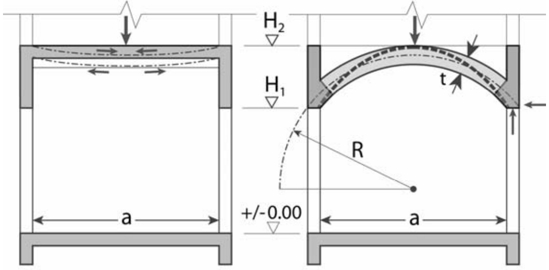

Fig. 3. Schematic conventional flat slab and vaulted roof, illustrating critical parameters

Optimization is used here as a framework tool to evaluate and compare the structural/mechanical performance, and in turn the life-cycle energy consumption of different structural forms. It was decided to reduce the optimization problem to a single-criterion assessment, by transforming structural requirements into constraints. In this way, complicated and often arbitrary criterion-weighting procedures are avoided. The principal objective of the optimization framework, then, is to minimize energy consumption in the two life-cycle building phases analyzed (i.e. pre-use and use phases) while maintaining structural stability and serviceability.

The optimization model is thus defined as follows:

Objective: to quantitatively determine energy efficient structural forms that minimize lifetime energy “costs”.

Design Variables: 1) The geometric parameters defining the structural roof shape.

2) The required material quantities (principally concrete and steel).

Constraints: The allowable domain for each parameter is represented by *structural* and *non-structural* influences. *Structural* constraints are the basic stability requirements (equilibrium equations) and resistance to dynamic lateral seismic loads. For vaults, allowable lateral thrust are limited, and for shells, buckling needs are to be avoided. Properties of materials are introduced as inputs to the structural optimization. *Non-structural* constraints are represented by maximum and minimum acceptable roof heights, vault spring point, plan area to be covered, and location and type of supports.

Based on the premise that an efficient structural form fitting these constraints may allow substantial reductions in energy-intensive material use and in turn total energy requirements, the process will be divided in basically four steps, (*Fig. 4*): 1) Preliminary efficient structural form exploration, 2) Embodied energy (EE) minimization (and structural shape optimization), 3) Operational energy (OE) analysis, and 4) Life-cycle energy assessment (LCEA).

1+2) *Preliminary efficient structural form exploration and embodied energy minimization*: In order to identify structural shapes that minimize bending stresses, a structural optimization process is employed. However, in order to include the mechanical behaviour when analyzing and finding the efficient structural form, a combination of 'form finding' methods and structural optimization is applied. As defined by Bletzinger et al. [25], form finding methods are designed to determine structural shape from an inverse formulation of equilibrium. Within them, hanging models are generally used for creating structures in compression by inversion of tensile shapes. Its goal is to minimize bending. This method comes to replace the first step in classical structural optimization – geometric model generation, generally accomplished with computer aided geometrical design (CAGD), for example Bezier-spline and B-spline patches.

In such an approach, the numerical hanging model is used for the shape generation, and then it is inverted. This model begins from an undeformed reference structure (in this case a planar slab), and then generates the most efficient equilibrium shape by applying distributed loads (self weight). This method is primarily based on the Finite Element Method (FEM). A contemporary digital procedure that can produce efficient forms of funicular structures is the Evolutionary Structural Optimization (ESO) method [26].

Another option for shape generation is the implementation of computer aided tools based on Graphical (Active) Statics. These methods are not dependent on a particular initial reference structure, nor on specific material choices which may affect the results.

In both cases proposed, the generated efficient shape (in mechanical terms) should be further validated by a structural analysis which concerns additional loads not previously considered (such as lateral loads), where the general geometry as well as properties and quantities of materials play an important role. Such a structural analysis, as an integrated part of the optimization process, is performed through an implementation of the FEM (such as ANSYS). Only feasible options are further energetically assessed.

Initial embodied energy requirements are calculated based on values for individual building materials and components [4, 6, 27].

3) *Operational energy analysis:* The building's structural form and material composition can positively or negatively influence the amount of thermal energy required for maintaining comfort. Hence, operating energy costs must be assessed for significant changes in the shape of the building that modify the internal air space and/or orientation, altering for instance solar exposure. Active thermal simulation employing commercially available software (e.g. Quick, IDA Indoor Climate & Energy) is thus performed to quantify the operational energy requirements for heating and cooling for each significant change in the geometry of the roof.

4) *Life cycle energy assessment:* The model proposed here is based on LCA principles [24]. Total energy consumption during the life cycle phases can be expressed as a sum of the partial energy requirements. The lifetime operational energy requirements derived from simulations is then summed together with the total embodied energy of the given configuration in order to calculate its cumulative life-cycle energy use. Alternatives that present lower values of whole life energy consumption are selected, others are automatically discarded. In this way, a set of optional structural forms is proposed.

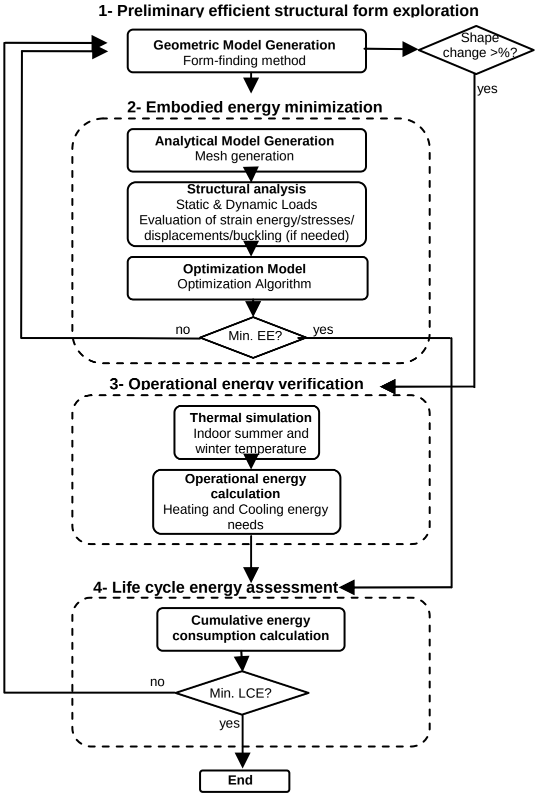

Fig. 4. Flow diagram of optimization methodology

6. Final considerations

Achieving greater levels of energy efficiency in the building sector is a goal for architects, engineers and researchers. This paper presents a methodological framework for analyzing structural roof forms, and for evaluating their potential to reduce energy consumption in buildings. The proposed methodology may serve as a decision support mechanism from the early phases of schematic building design, and can encourage environmentally-responsible decision making throughout the building process. This study is a part of an ongoing research, which will further develop the required tools and demonstrate the application of the methodology.

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