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Robustness Analysis of Kinetic Structures

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Abstract

The present paper considers robustness of kinetic structures. Robustness of structures has obtained a renewed interest due to a much more frequent use of advanced types of structures with limited redundancy and serious consequences in case of failure. Especially for these types of structural systems, it is of interest to investigate how robust the structures are, or what happens if a structural element is added to or removed from the original structure. The present paper discusses this issue for kinetic structures in architecture.

Keywords: Kinetic architecture, deployable structures, tensegrity, redundancy, robustness.

1. Introduction

Kinetic structures in architecture follows a new trend which is emerging in *responsive architecture* coined by Nicholas Negroponte when he proposed that architecture may benefit from the integration of computing power into built spaces and structures, and that better performing, more rational buildings would be the result (Negroponte 1975, Beesley, Hirosue, Ruxton and Trankle 2006). This kind of interactive spaces are built upon the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaptation within the contextual framework of human and environmental interaction (Fox 2001a, b, Kronenburg 2002). Deployable, foldable, expandable and reconfigurable kinetic structures can provide a change in the geometric morphology of the envelope by contributing to making it adaptable to e.g. changing external climate factors, in order to improve the indoor climate performance of the building. Structural solutions for kinetic structures have to consider in parallel both the *ways* and *means* for kinetic operability. The *ways* in which a kinetic structural solution performs may include among others, folding, sliding, expanding, and transforming in both size and shape. *The means* by which a kinetic structural solution performs may be, among others, pneumatic, chemical, magnetic, natural or mechanical (Fox 2001a, b). Kinetic structures have often a defined 'open-closed' or 'extended-contracted' body shape, i.e. transformations occur between two body shapes (Zuk and Clark 1970, Escrig 1996, Gantes 2001, Kronenburg 2002). Most of the previously developed kinetic structures have 'open-closed' or 'extended-contracted' body shapes based on scissor-like elements such as those proposed by the key designers/researchers (Piñero 1962), (Escrig 1985), (Hoberman 1993), (Calatrava 1981) and (Pellegrino and You 1997). Recently, proposals for adaptive kintic structures using scissor-like elements have been given, i.e. structures where transformations occur between more than two different shapes to constitute more flexible shape alternatives (Akgün, Haase and Sobek 2007, Inoue 2007). In general these kinetic structures have a low structural efficiency with respect to load bearing capacity versus self-weight, and may deform to a large extent due to low structural stiffness. Therefore these structures are still not becoming an acceptable alternative for construction compared to other strucurral systems and much research is going on to improve the efficiency of kinetic structural systems (Temmerman 2007, Liew, Vu and Krishnapillai 2008). However, when such new structural systems are proposed for application, there is always a question of how robust the structure is, or in other words, what happens if e.g. a scissor-like element is added to or removed from the original structural system.

Recently, robustness of structural systems has obtained a renewed interest due to a much more frequent use of advanced types of structures with limited redundancy and serious consequences in case of failure. The interest has also been facilitated due to recently severe structural failures such as that at Ronan Point in 1968 and the World Trade Centre towers in 2001. In order to minimise the likelihood of such disproportionated structural failures many modern building codes (CEN 2002b, a) consider the need for robustness in structures and provides strategies and methods to obtain robustness. One of the main issues related to robustness of structures is the definition of robustness. The most general definitions are very similar to each others particularly those taken from codes despite the use of different terms (robustness, structural integrity, but also progressive collapse prevention). These definitions are focussed on the prevention from an escalation of damage within the structure, given a certain initial (localised) failure/damage. During the last decades a variety of research efforts have attempted to quantify aspects of robustness such as redundancy and identify design principles that can improve robustness (Baker, Schubert and Faber 2007, Canisius, Sørensen and Baker 2007). Due to many potential means by which a local collapse in a given structure can propagate from its initial extent to its final state, there is no universal approach for evaluating the potential for disproportionate collapse, or for robustness (Ellingwood, Smilowitz, Dusenberry, Duthinh and Carino 2007). Today the importance of reliable design procedures leading to conceive redundant and robust structures is widely recognized. The terms robustness and redundancy are often used as synonymous, and even though a relationship among them usually holds, they denote different properties of the structural system. In fact, structural robustness can be viewed as the ability of the system to suffer an amount of damage not disproportionate with respect to the causes of the damage itself. Structural redundancy can instead be defined as the ability of the system to redistribute among its members the load which can no longer be sustained by some other members in consequence of their damage (Frangopol D.M. and J.P. 1987). The present paper outlines the effects of prescribed failure scenarios on both robustness and redundancy and robustness of kinetic structures is finally discussed.

2. Kinetic structures in architecture – responsive architecture

Generally, kinetic structures in architecture can be defined as buildings and/or building components with variable mobility, location and/or geometry (Fox 2001a), i.e. kinetic architecture can refere to buildings or structures with variable location or mobility such as portable buildings like caravans, tents and prefabricated barracks (Kronenburg 2002). However, it can also be buildings or structures with variable geometry or movement, i.e. soft form buidlings with transforamtion capacity made by membrane structures, cable-nets pneumatic structures, or rigid form buildings with deployable, foldable, expandable or rotating and sliding capacity of rigid materials which are connected with joints (Güçyeter 2004, Korkmaz 2004).

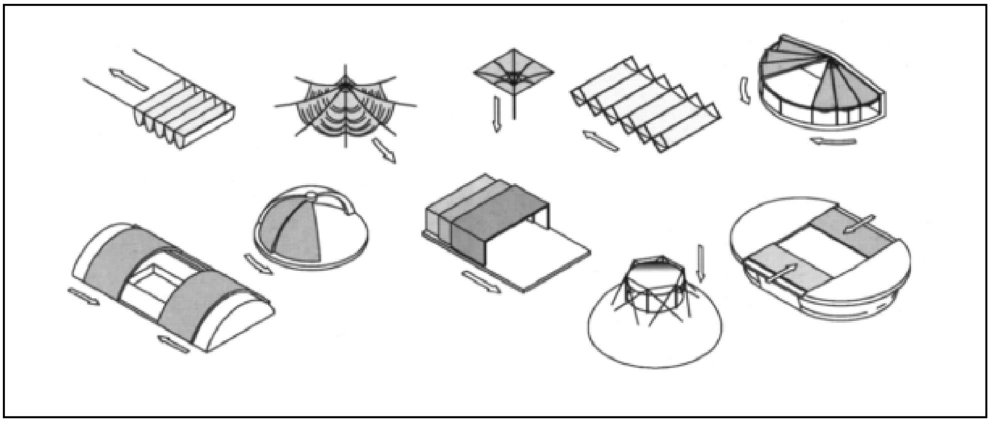

Figure 1: Types of various kinetic systems (Güçyeter 2004).

Kinetic structures can also be classified according to their structural system. In doing so, four main groups can be distinguished: spatial bar structures consisting of hinged bars, foldable plate structures consisting of hinged plates, strut-cable (tensegrity) structures and membrane structures (Hanaor and Levy 2001, Temmerman 2007). These structural systems have been classified by their morphological and kinematic characteristics in figure 2 (Hanaor, et al. 2001). Much research has been done with respect to improve the efficiency of these kinetic structural systems which can faciliate a flexibility in bulding design and give rise to a search for responsive architecture which can physically convert themselves to adapt to the ever-changing requirements and conditions (Zuk, et al. 1970, Fox 2001a, Beesley, et al. 2006, Temmerman 2007, Liew, et al. 2008). This could theoretically be buildings consisting of rods and strings which would bend in response to wind, distributing the load in much the same way as a tree. Similarly, windows would respond to light, opening and closing to provide the best lighting and heating conditions inside the building. However, any approach to producing responsive, adaptive achitecture must consider architectural and engineering knowledge to ensure robustness of the structure.

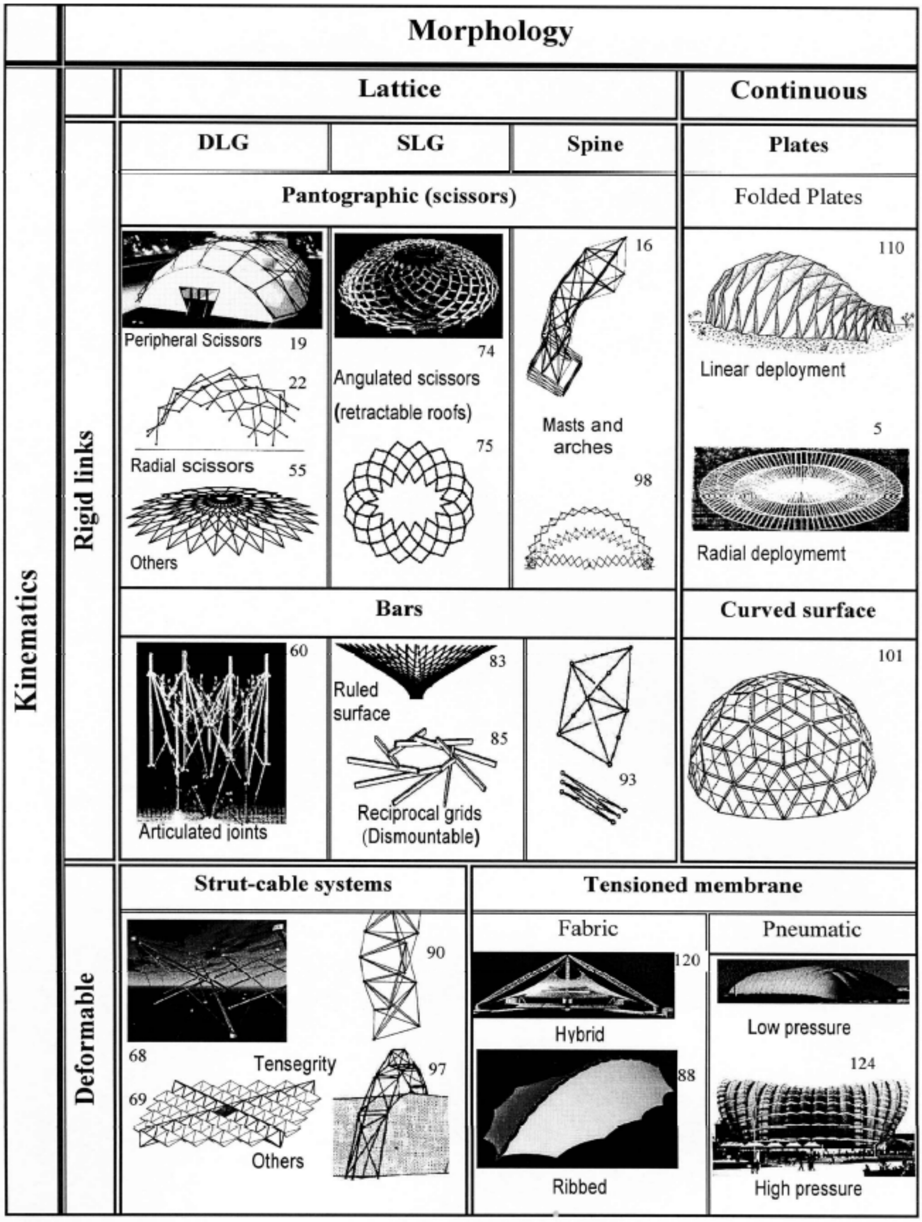

Figure 2: Deployable structures. Numbers indicate references in (Hanaor, et al. 2001).

3. Framework for robustness of structures

The requirement for robustness is specified in most buildings codes in a way like the general requirements in the two Eurocodes: *EN 1990 - Basis of Structural Design* (CEN 2002a) and *EN 1991-1-7 - Accidental Actions* (CEN 2006). *EN 1990 - Basis of Structural Design* (CEN 2002a) provides principles, e.g. it is stated that a structure shall be 'designed in such a way that it will not be damaged by events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause'. It also states that potential damage shall be avoided by 'avoiding, eliminating or reducing the hazards to which the structure can be subjected; selecting a structural form which has low sensitivity to the hazards considered; selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localized damage; avoiding as far as possible structural systems that can collapse without warning; tying the structural members together'. *EN 1991-1-7 - Accidental Actions* (CEN 2006) provides strategies and methods to obtain robustness. Actions that should be considered in different design situations are: 1) designing against identified accidental actions, and 2) designing against unidentified actions (where designing against disproportionate collapse, or for robustness, is important).

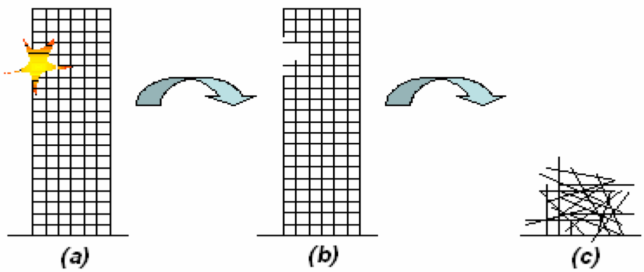

Figure 3: Illustration of the basic concepts in robustness (CEN 2006) .

Figure 3 illustrates the basic concepts in robustness:

a) Exposures which could be unforeseen unintended effects and defects (incl. design errors, execution errors and unforeseen degradation) such as
    - unforeseen action effects, incl. unexpected accidental actions
    - unintended discrepancies between the structure's actual behaviour and the design models used
    - unintended discrepancies between the implemented project and the project material
    - unforeseen geometrical imperfections
    - unforeseen degeneration
b) Local damage due to exposure (direct consequence of exposure)
c) Total (or extensive) collapse of the structure following the local damage (indirect consequence of exposure

Robustness requirements are especially related to step from b) to c), i.e. how to avoid that a local damage develop to total collapse, i.e. robustness is meant to avoid failures caused by errors in the design and construction, lack of maintenance and unforeseeable events.

During the last decades there has been a significant effort to develop methods to assess robustness and to quantify aspects of robustness. An overview of these methods is given in (Baker, et al. 2007). The basic and most general approach is to use a risk analysis where both probabilities and consequences are taken into account. Approaches to define a robustness index can be divided in the following levels with decreasing complexity (Vrouwenvelder and Sørensen 2009) :

- A risk-based robustness index based on a complete risk analysis where the consequences are divided in direct and indirect risks
- A probabilistic robustness index based on probabilities of failure of the structural system for an undamaged structure and a damaged structure
- A deterministic robustness index based on structural measures, e.g. pushover load bear ing capacity of an undamaged structure and a damaged structure.

Due to many potential means by which a local collapse in a given structure can propagate from its initial extent to its final state, there is no universal approach for evaluating the potential for disproportionate collapse, or for robustness (Ellingwood, et al. 2007). However, for reduction of the risk of collapse in the event of loss of structural element(s), a structural engineer may take necessary steps to design a collapse-resistant structure that is insensitive to accidental circumstances. This means that the following structural traits should be incorporated in the design (Ellingwood, et al. 2007):

- *Redundancy*: incorporation of redundant load paths in the vertical load carrying system.
- *Ties*: using an integrated system of ties in three directions along the principal lines of structural framing.
- *Ductility*: structural members and member connections have to maintain their strength through large deformations (deflections and rotations) so the load redistribution(s) may take place.
- *Adequate shear strength*: as shear is considered as a brittle failure, structural elements in vulnerable locations should be designed to withstand shear load in excess of that associated with the ultimate bending moment in the event of loss of an element.
- *Capacity for resisting load reversals*: the primary structural elements (columns, girders, roof beams, and lateral load resisting system) and secondary structural elements (floor beams and slabs) should be designed to resist reversals in load direction at vulnerable locations.
- *Connections (connection strength)*: connections should be designed in such way that it will allow uniform and smooth load redistribution during local collapse

- *Key elements*: exterior columns and walls should be capable of spanning two or more stories without bucking, columns should be designed to withstand blast pressure etc.
- *Alternate load path(s)*: after the basic design of structure is done, a review of the strength and ductility of key structural elements is required to determine whether the structure is able to "bridge" over the initial damage.

These listed characteriscs can be used for designing against identified accidental actions, and designing against unidentified actions according to *EN 1991-1-7 - Accidental Actions* (CEN 2006).

4. Robustness of kinetic structures

Considering the different types of kinetic structures in figure 2 the robustness issue seems to be important to discuss for structures based on a lattice system or a strut-cable system. This kind of structures has structural systems which can be modelled as series or parallel systems, see figur 4.

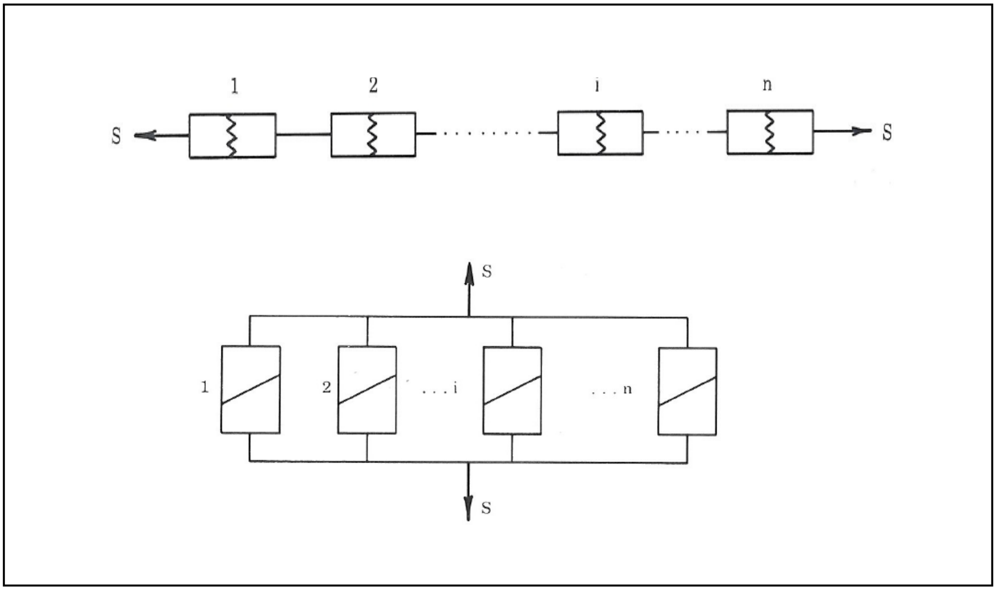

Figure 4: Diagram for series and parallel systems subjected to a load *S*.

The combination of failure elements in a series system corresponds to e.g. a statically determinate (non-redundant) structure with *n* structural elements. For such a statically determinate structure, a weakest link system, it is clear that the whole structural system fails as soon as any structural element fails, i.e. the structure has no load-carrying capacity after failure of one of the structural elements. For each structural element several failure modes are possible, e.g. material yielding and buckling failure. The parallel system in figure 4 can represent a statically indeterminate (redundant) structure with *n* structural elements which can have several modes such as material yielding material yielding and buckling failure. For such a statically indeterminate (redundant) structure it is clear that the whole structural system will not always fail as soon as one of structural element fails, because the structure has a load carrying capacity after failure of some of the structural elements. This load-carrying capacity is obtained after a redistribution of the load effects in the structure after the element failure. Failure of the entire redundant structure will then often require failure of more than one structural element. (It is in this connection very important to define exactly what is understood by failure of the structural system). Since a redistribution of the load effects has to take place in a redundant structural system after failure of one or more of the structural elements it becomes very important in parallel systems to describe the behaviour of the failed structural elements after failure has taken place. If the structural element has no strength after failure the element is said to be *perfectly brittle*. If the element after failure has a load-bearing capacity equal to the load at failure, the element is said to be *perfectly ductile.* The following sections will discuss redundancy and brittle/ductile with respect to kinetic structures

4.1. Redundancy

The lattice type structures are usually designed with several diagonals transferring the loads to a given number of supports. Therefore a redundant structure exists with alternative load paths in the load carrying system. Structural redundancy is the quality of a system to redistribute among its members the load which can no longer be sustained by some other members due to a failure state, i.e. if one or more elements fail, the remaining structure is able to redistribute the load and thus prevent a failure of the entire strucutre, i.e.parallel system. Redundancy is usually associated with the degree of static indeterminacy and represents a key factor for structural robustness. Often it is assumed that static indeterminacy are more robust than less static indeterminacy structures, and therefore one may assume that lattice type structures are born with a high degree of robustness. However, it has been demonstrated that the degree of static indeterminacy is not a consistent measure for structural redundancy (Frangopol D.M., et al. 1987). It can been shown, that structural redundancy depends on many factors, such as structural topology, member sizes, material properties, applied loads and load sequence, among others. Therefore, structures with lower degrees of static indeterminacy can have a greater redundancy than structures with higher degrees of static indeterminacy (Frangopol D.M., et al. 1987). Also som recently major collaps of structures have shown that a low degree of static indeterminacy was awarded when part of a structure collapsed. The structure, Ballerup Super Arena in Copenhagen, consisted of glued laminated timber trusses in the primary load bearing system. However, a human error in design of the joints of the trusses faciliated a collapse in 2003 where two out of 12 main trusses failed. The transverse purlins (secondary system) were designed in such a way (series system modeling) that progressive collapse of the whole roof should not occur in case of failure of single main truss. The roof system can therefore be considered as a robust system in the sense that the collapse whole roof did not collapse. This seems to be a good strategy in case of design/human errors occurring in many places / joints (high correlation) for new, unconventional structures. The same quality with respect to low degree of low degree of static indeterminacy was also seen in the case of the partial collapse of the Charles de Gaulle Airport Terminal in 2004. Again there were limited interconnections between the bays, and only one bay collapsed. The collapse was caused by poor workmanship and design errors, and increased redundancy might have resulted in a progressive collapse of more bays. A third example where high degree of static indeterminacy did not generate a robust structure was seen when the Bad Reichenhall Ice-Arena had a total roof collapse in 2006. The primary structural system consists of very high box-girder beams with no previous experience. The secondary system was relatively stiff implying that the roof could be considered as a parallel system. Design, execution and operational errors in all main beams implied that the load bearing capacity was significantly lower than required and the roof collapsed with a snow load about ½ of the design snow load. The roof system can therefore not be considered as a robust system in the sense that the whole roof collapsed. Therefore with respect to kinetic structure more research is required to investigate about this kind of structures in general will benefit from a high degree of static indeterminacy.

4.2 Ductility

In general kinetic structures consist of slender steel compression members (pipes, rod) which sometimes are combined with cables in strut-cable system (tensegrity structures). Compression members will have a brittle behaviour due to buckling failure modes. On the other hand tension members will have a ductile behaviour due to the characteristics of the material. Most structural engineers have the intuitive understanding that robustness of structures can be improved by introducing ductile members, i.e. the number of ductile members increases robustness of a structural system when it can be modelled as a parallel system. However, this is not the fact when the stochastic behaviour of load and structural members are considered. In (Baker, et al. 2007) results have been presented showing that robustness decreases when the uncertainty of loading or correlation between strength of members is increased. Therefore for a more detailed study of robustness related to the brittle/ductile issue with respect to kinetic structures a stochastic framework has to be used.

4. Conclusions

When a new structural system is proposed for application, there is always a question of how robust the structure is, or in other words, what happens if e.g. a structural element is added to or removed from the original structure. It is an issue which is interesting to discuss with respect to structures with a low degree of degree of static indeterminacy. Therefore the aim of the present paper has been to point out the robustnees issue for kinetic structures often born with a low degree of static indeterminacy. The paper states that redundancy and material characteristics (brittleness/ductility) for this kind of structures have to be investigated closer in a stochastic framework.

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