Quantifying Structural Flexibility for performance based life cycle design of buildings

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ABSTRACT
When we try to specify minimum performance levels for the whole life cycle of a building we have to face the problem of how to deal with the uncertainties of future functional use. In stead of specifying minimum functional requirements we could opt to specify minimum levels of flexibility. To achieve this, it becomes necessary to quantify and compare “flexibility”. To do this flexibility is defined more precise. Because the building structure is usually the longest lasting building layer the possibilities to quantify the flexibility of the building structure, “Structural Flexibility”, is looked at in more detail. A definition of Structural Flexibility is given and a framework to measure and compare Structural Flexibility is discussed.

1. Minimum functional performance levels.
In Performance Based Design it is necessary to define minimum requirements and to use suitable models for behaviour. These models should include the expected service life of the building. Reliable checks must ensure that the proposed design solutions will actually meet these minimum performance levels, not only at the start but also during the Service Life of the building.

Because the Service Life of a building also depends on its functional qualities (Functional Working Life), it is essential to specify minimum levels of functional requirements. However, future user demands (specially for second and later users) have a large degree of uncertainty. Because of this, flexibility is often used as a strategy in the Life Cycle Design of buildings. Two different fundamental ways to respond to change or uncertainty can be distinguished:

- Active Flexibility: The ability to respond by changing, reacting or adapting. In building we call this Adaptability

- Passive Flexibility: There is no need to react, because of sufficient tolerance or capacity. This second type of flexibility is in other disciplines sometimes referred to as “robustness”. For various reasons here the word Flexibility is used for passive flexibility.
In stead of specifying minimum functional requirements for a given (fixed) functional use, we can opt to specify minimum levels of Flexibility (and / or Adaptability) in order to ensure a better way of coping with future changing demands.

2. Framework of definitions

The words flexibility and adaptability have become very popular. To prevent the delution of meaning, we need to define them very precise. Research undertaken at the TU/e with regard to the relations of the building structure with the other building layers: envelope, services, access and space plan (including the way the space is used), has resulted in a clear frame-work of definitions of the different kinds of Flexibility.

2.1 A flexible building

In general, a Flexible Building can be defined as a building with the (passive or active) capacity to accommodate, in a relatively easy way, (future) changes. This definition poses the problem of how to regard, or how to define “relatively easy”. In the chosen definitions a change to a certain building layer is regarded as “relatively easy” if it can be achieved without the necessity to affect or change other building layers as well.

For example: A building with a load-bearing elevation wall combines the layers of Structure and Envelope. It is not possible to change the Envelope layer without also changing the Structure. Regarding this aspect the building is not flexible. It is possible however, that the same building is flexible with regard to other building layers, for example the Servant elements or the Space plan (partition walls).

Flexibility involves many levels. However, with the use of a simplified building model, [for example Brand 1994; Leupen 2002], Flexibility and Adaptability can be defined at building level by looking at the relations of the building layers with eachother.

Adaptability of a given building layer (f.i. structure, services, envelope etc.) is defined as:

The capacity of the building layer to accommodate changes to the layer itself, without or with minor consequence to other building layers. (This implies that other building layers can obstruct the Adaptability of the layer in question.) For example: Structural Adaptability means that the structure itself can (easily) be changed. (“Active Flexibility”)

Flexibility is defined likewise. Flexibility of a given building layer means:

The property of that building layer to accommodate changes to other building layers, without the necessity to change that particular building layer itself. For example Structural Flexibility means that the structure accommodates changes to one or more other building layers (for example space plan, services) without the need to change the structure itself. (“Passive Flexibility”)

3. Adaptability and flexibility relations

The possible flexibility and adaptability relations are considered at building level. They can be derived from the adopted building model. These theoretical relations of the building layers are shown in [fig. 1]. Within the building 10 primary relations (two way arrows) can be distinghuised.
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In this model, the arrows towards a building layer represent the relations influencing the adaptability of that particular layer. The arrows leaving from a building layer represent the flexibility of that particular building layer (accommodating possible changes to other building layers).

The four flexibility relations of the structure are drawn in bold. (The flexibility relation of the structure with its Location (dotted line) denotes the aspect of Mobility of the structure.). Note that adaptability at building level is not possible without (a certain degree of) flexibility of other building layers.

At a deeper level, within a building layer, it also becomes clear that adaptability of certain elements is not possible without sufficient flexibility of other elements. For example an Adaptable Structure, in which columns can be added, removed or changed in different positions is only possible with sufficient flexibility of other elements, for example the beams, by providing sufficient bearing capacity.

An example of flexibility of the structure at building level is given in (Fig. 2). The prefabricated holes in the concrete beam make it possible to change or adapt the position of the service ducts.

Fig. 1 Theoretical adaptability and flexibility relations at building level.

Fig. 2 Flexibility of the structure: Service ducts can be adapted and can cross the concrete beams.
where needed. (Hospital Laboratory, Lyon, France).

4. Structural Flexibility

Structural Flexibility is regarded as one of the most essential forms of flexibility, because in general the structure’s qualities and relations are very influential in the decision process regarding refurbishment or demolition of our existing building-stock. To investigate the structure’s flexibility three main questions rising from the structures primary functions and qualities need to be answered:

- Is the building layer Structure sufficiently independent of other building layers?
  A: Does the structure share parts with other building layers?
  B: How are the connections with other building layers. Are they reversible (bolted, etc)?

- Does the structure provide sufficient space to each of the other building layers?

- Does the structure provide sufficient load-bearing capacity for each of the other building layers?

4.1 Quantifying Structural Flexibility

These three qualities of the structure, independence, space, and load-bearing capacity, are each evaluated with respect to the other four building layers. A large provided space and bearing capacity together with a high degree of independence from other building layers, will result in a high score on Structural Flexibility.

The following (simplified) matrix [fig. 3] shows the principle flexibility relations of the structure with the other building layers:

The aim of the research is to investigate, evaluate and quantify each relation, and finally come to resulting scores $R_{layer_i}$, representing the Structural Flexibility with regard to each of the other building layers. The resulting scores indicate to which degree the structure accommodates (not blocks or obstructs) the Adaptability of the other building layers. To achieve this overall indicators and partial indicators representing the qualities of these relations of the structure with the other building layers are defined and further investigated.

An example of a partial structural flexibility indicator is given in [Table 1].
Table 1. Partial Indicator: Allowable Life Floor Load

<table>
<thead>
<tr>
<th>Flexibility class: Life Floor Load</th>
<th>Allowable Life Floor load $P_{rep}$ (kN/m²)</th>
<th>Minimum values for life floor loads depending on the building functions according to Dutch building regulations</th>
<th>Partial Flexibility indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>I  Not Flexible</td>
<td>$P_{rep} \leq 1.75$</td>
<td>Houses</td>
<td>0.2</td>
</tr>
<tr>
<td>II Limited Flexibility</td>
<td>$1.75 &lt; P_{rep} &lt; 2.5$</td>
<td>Apartment buildings</td>
<td>0.4</td>
</tr>
<tr>
<td>III Average Flexibility</td>
<td>$2.5 \leq P_{rep} &lt; 4.0$</td>
<td>Schools, Hotels, Hospitals, Offices</td>
<td>0.8</td>
</tr>
<tr>
<td>IV Very Flexible</td>
<td>$4.0 \leq P_{rep} &lt; 5.0$</td>
<td>Shops, Museums, Public Buildings</td>
<td>1.0</td>
</tr>
<tr>
<td>V  Extreme Flexible</td>
<td>$5.0 \leq P_{rep} &lt; 10.0$</td>
<td>Industrial Buildings, Warehouses</td>
<td>1.0 - 2.0 (Depending on value of $P_{rep}$)</td>
</tr>
</tbody>
</table>

The example shows a partial indicator denoting the structure’s qualities with regard to load bearing capacity in relation to the building layer Space Plan. This load bearing capacity is classified in five different categories, from “not flexible” to “extremely flexible”. After scoring and weighing the partial indicators (still subject of the research) the aim is to visualise the resulting scores. An example of the quantification of the Structural Flexibility of a given structure in a single multi-criteria chart is given in [Fig. 4]

Fig 4: Multi-criteria Structural Flexibility Chart (From centre outwards: Flexibility class I (Not Flexible), to V (Extremely Flexible).

5. Discussion.

With the proposed definition of Structural Flexibility (and Structural Adaptability) together with the proposed framework for evaluation it will become possible to quantify, evaluate and compare both existing as well as newly designed building structures with regard to their Flexibility. A high Structural Flexibility will increase the building’s performance by allowing for possible future adaptions of the building layers, for example caused by changing user requirements. This might result in a higher probability of a long Functional Working Life of the building. The relations between on one hand the realised Structural Flexibility and on the other hand the expected service life of the building structures needs further research.

6. References


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