SEISMIC ANALYSIS OF EXISTING BUILDINGS WITH DIFFERENT CONSTRUCTION UPGRADES

Jurij Jancar 1, Bruno Dujic 2

ABSTRACT: This paper deals with an important theme about possibilities of upgrading existing buildings with additional stories made of light prefabricated systems. The purpose of the study was to analyse the seismic response of an existing three-storey reinforced concrete building upgraded with three different construction systems: 1) rigid box of cross laminated (Xlam) timber panels, 2) braced steel frame with RC slabs, and 3) combined steel frame with Xlam timber wall infills and floor diaphragms. Modal analysis and linear dynamic analysis were performed for the combined existing and upgrade structures of all three types using the exact modelling and two simplified models in order to study the possibility of simplification of the earthquake analysis and different impacts of the upgrade structures on the existing building. The analyses show the major differences between the simplified models in comparison to the realistic one. Comparisons of different properties and possible problems have been pointed out. Additionally some requirements from the Eurocode dealing with the possible types of seismic analysis and application of the q-factor are discussed.

KEYWORDS: Cross laminated timber, hybrid structures, simplified seismic analysis, amplification of displacements

1 INTRODUCTION

In the engineering practice designers are often faced with projects that involve reconstruction, renovation and conversion of purpose. One of the most cost effective ways for renovation of existing structure is to upgrade it with reasonable number of additional stories. In this case it is possible to avoid some of the major investments such as land purchase and construction of utility equipment, while the renovation expenses can be covered with the profit of newly obtained residential or business areas. Adding some extra stories to the existing structures due to the shortage of space intended for new facilities in the urban centres is probably the only way to increase useful area of any type.

With increasing interest in upgrading there are some questions raised between designers considering problems of interaction between existing and new structure especially if weight and stiffness are very different. Usually superstructure is planned to be from light materials and more flexible construction while existing structure is much more rigid and heavy. Therefore in seismic design questions appear frequently about the accuracy of the calculation model, what type of computational analysis is necessary and what possibilities (and consequences) of using simplified models are.

For the purpose of this study, a three-storey building of reinforced concrete (RC) was designed, which was then upgraded with a superstructure of a different construction system. Using this example possibilities and mistakes of applying simplified computational models were studied. All of the analyses were done in ETABS (CSI, 2004) application.

![Figure 1: Mathematical model of the basic structure](image)

Furthermore, three different types of upgrades were modelled at the top of the basic RC structure. Observations were focused at the differences between the modal analysis results.
The main goal of this study was to get a conclusion about the possibility of using simplified models for seismic analysis and to recognize what is the global seismic behaviour of different types of upgraded structural systems, what is their influence on the existing RC structure and what are EC8 requirements when hybrid structural systems have to be dynamically analyzed.

2 SIMPLIFIED SEISMIC ANALYSIS

In general it is possible to design building parts separately for the basic structure and for the upgrade in terms of static loads. But when we deal with dynamic loads and seismic design, this simplification becomes more problematic. This idea is based on the assumption that the basic structure is so rigid, that during a seismic event it would shake like foundation soil and that its deformations in comparison to the more flexible superstructure at the top could be neglected. On the basis of such assumptions the seismic analysis is often performed separately for the upper and for the lower structure. But to obtain correct results for the basic structure that is being upgraded, it is necessary to take into account the right impact of this upgrade on the original structure. One possibility is to add the mass of the upgrade evenly distributed over the top of the basic structure. However, there appears a question about the error of such simplification, because the mass of the superstructure is not applied at the real height of its centre of gravity.

2.1 SIMPLIFIED MODELS

To recognize the differences two different calculation models were considered. The first one had the mass of the upgrade evenly distributed over the roof of the basic structure while in the second model it was attached at the real height of the centre of gravity with absolutely rigid connections. Additionally, the exact model of the upgrade structure was created and attached to the basic one. To obtain a complete comparison and overview of different modelling and analyses, the results were compared with the seismic response of the original RC structure in both directions in terms of the increase of base reactions, overturning moments and displacements at the top of basic structure. The design of the upgrade structure was in general the same as for the basic one except that it was made from more light and flexible cross laminated wooden elements. For all four models modal response spectrum analysis was done while the main input data for EC8 response spectrum were:

- ground acceleration: $a_g = 0,25g$
- soil type: B: $S = 1,2$
- behaviour factor: $q = 1,0$

The obtained results are presented in Table 1.

2.2 COMPARISON OF RESULTS

The comparison shows that results of the simplified models are more conservative than those obtained from the more complex and accurate model. Results presented in Table 1 display relatively good match in seismic forces, but there is a large difference in overturning moments between the model with uniformly distributed upgrade mass over the top of the basic structure and the accurate hybrid model of light upgrade and heavy basic structure. This outcome is logical as in reality the mass of the upgrade is acting on a greater height. Additionally it was observed that displacements match quite well with the second model - structure with uniformly distributed upgrade mass over the roof of the basic structure. In the third model displacement results show an increase of rigidity probably due to the absolutely rigid links for the mass connection, which affected the deformability of the upper part of the basic construction.

Modal analysis has been performed separately for the upgrade as self standing structure and it was found that displacements in comparison to the upgrade structure mounted at the top of the basic one are four times smaller. This difference proved that the upgrade structure is loaded with much higher forces and therefore it should not be analyzed separately from the basic structure. An amplification of acceleration occurred at the top of the base structure; therefore, the ground acceleration input in the separate analysis of the upgrade structure is not correct. It is concluded that results obtained from simplified models are not reliable enough to use them in everyday practice.

Table 1: Comparison of modal analysis results of different calculation models

<table>
<thead>
<tr>
<th></th>
<th>Basic RC structure</th>
<th>Structure with uniformly distributed mass of upgrade over the roof</th>
<th>Structure with mass of upgrade connected at the height of its centre of gravity</th>
<th>Model with exact upgrade structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Pa$ [kN]</td>
<td>7260</td>
<td>10660</td>
<td>10616</td>
<td>9656</td>
</tr>
<tr>
<td>Increase</td>
<td>/</td>
<td>1,47</td>
<td>1,46</td>
<td>1,33</td>
</tr>
<tr>
<td>$Pa$ [kN]</td>
<td>6517</td>
<td>9390</td>
<td>9233</td>
<td>8873</td>
</tr>
<tr>
<td>Increase</td>
<td>/</td>
<td>1,44</td>
<td>1,42</td>
<td>1,36</td>
</tr>
<tr>
<td>$M_r$ [kNm]</td>
<td>43601</td>
<td>70204</td>
<td>86030</td>
<td>90614</td>
</tr>
<tr>
<td>Increase</td>
<td>/</td>
<td>1,61</td>
<td>1,97</td>
<td>2,08</td>
</tr>
<tr>
<td>$M_r$ [kNm]</td>
<td>48930</td>
<td>80256</td>
<td>97486</td>
<td>101193</td>
</tr>
<tr>
<td>Increase</td>
<td>/</td>
<td>1,64</td>
<td>1,99</td>
<td>2,07</td>
</tr>
<tr>
<td>$\nu_0$ [°/°]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase</td>
<td>/</td>
<td>1,63</td>
<td>1,09</td>
<td>1,77</td>
</tr>
<tr>
<td>$\nu_0$ [cm]</td>
<td>0,95</td>
<td>1,55</td>
<td>1,04</td>
<td>1,68</td>
</tr>
<tr>
<td>Increase</td>
<td>/</td>
<td>1,62</td>
<td>1,01</td>
<td>1,77</td>
</tr>
</tbody>
</table>

3 POSSIBLE UPGRADE SYSTEMS

When upgrading an existing building, the upper structure must be as light as possible and it has to be easily and quickly assembled. It is also very important that the assembly is quiet, clean and un-disturbing so that the building can serve its purpose while it is being upgraded. Special attention must be paid to the superstructure load bearing system, which has to enable efficient load transfer to the lower structure. For the purpose of this research, three types of upgrade structures have been identified. All of them are three stories and have the same layout as the basic structure. Details are presented in the following paragraphs.
For each upgrade structural system, modal and linear
dynamic analyses were performed on the exact model of
the hybrid system where the upgrade was attached to the
top of base RC structure. The input data for the linear
dynamic analysis was the earthquake that occurred in
Montenegro in 1979.

3.1 UPGRADE STRUCTURE FROM XLAM
TIMBER ELEMENTS
The main advantage of timber structure from cross
laminated plates (Xlam) is its very high load bearing
capacity and stiffness relative to its density. For the
purpose of modelling and calculation the characteristics
of KLH Massivholz elements were taken into account.
The KLH system is fully prefabricated so that only
assembly and finishing take place on the construction
site. Very positive characteristic is that a box system
transfers loads to the existing building uniformly over
the walls, where overloaded parts of the existing
structure or places with insufficient load-bearing
capacity could be easily over bridged. According to
present requirements in EC8 the highest behaviour factor
(q) for glulam timber system could be 2 in the case
of regular buildings. When seismic analysis is done for
a hybrid system, the lower q factor of the two structural
systems has to be applied. In combination of RC base
regular wall structure (q=3) and Xlam upgrade structure
(q=2) the combined model factor for the hybrid structure
(Figure 2) has to be not greater than 2.

3.2 BRACED STEEL FRAME UPGRADE
STRUCTURE
For the purpose of this research, a three storey braced
steel frame structure was designed with composite steel
concrete slabs and very light prefabricated roof. A high
strength-to-density ratio of steel justifies its use for
upgrading existing buildings.
Braced steel frame structure transfers loads locally and
this could be an advantage in the case where stronger
construction parts of the basic building are available for
support of the upper structure at the points of attachment.
But in most cases locally loaded existing buildings are
problematic if they are not strong enough or if they were
not designed to resist higher local stresses. These could
negatively influence the seismic resistance because the
areas with very high stress concentrations are especially
vulnerable under dynamic loading.

3.3 COMBINED STEEL FRAME STRUCTURE
WITH TIMBER XLAM WALL INFILLS AND
FLOOR DIAPHRAGMS
The third type of construction system for upgrade was
chosen with the goal to combine the benefits of the
systems presented in sections 3.1 and 3.2. Therefore, a
hybrid system made of steel columns and beams
connected with Xlam timber panels used for wall infills
and floor diaphragms has been designed. Heavy concrete
slabs and flexible braced frame were in this case
replaced by cross laminated (Xlam) timber panels.

This combination made the newly formed structure
lighter and much more rigid, which reduced the “whip
effect”; i.e., the amplification of horizontal displacement
at the top of the upgraded building. The maximum
behaviour factor which can be taken into account in this
case is q = 2, the minimum of all load-bearing system
types present in the hybrid construction (Figure 4).
4 RESULTS OF MODAL AND LINEAR DYNAMIC ANALYSES

The modal analysis was focused on comparison of seismic forces and horizontal displacements of selected types of structural upgrades. Elastic and design base shears calculated for all types of selected structures are presented in Table 2 together with the total weight of the composed structure and maximum displacement of the basic and the upgrade structures.

The linear dynamic analysis was focused on global structural behaviour and differences between horizontal time history response with presenting displacement at the top of basic RC structure (point B) and displacement at the top of upgrade structure (point A) during a seismic event (Figures 5a, 5b and 5c).

Table 2: Results of modal analyses of different composed structural systems in comparison with the basic RC structure

<table>
<thead>
<tr>
<th>Basic RC structure</th>
<th>Upgrade with box of Xlam timber panels</th>
<th>Upgrade with steel braced frame</th>
<th>Upgrade with hybrid steel frame and Xlam panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$ [kN]</td>
<td>15106</td>
<td>19733</td>
<td>20978</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>1.31</td>
<td>1.39</td>
</tr>
<tr>
<td>$Q$ [kN]</td>
<td>2985</td>
<td>4825</td>
<td>4825</td>
</tr>
<tr>
<td>$G + Q$ [kN]</td>
<td>18001</td>
<td>24558</td>
<td>25803</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>1.36</td>
<td>1.43</td>
</tr>
<tr>
<td>$F_{b,x,el}$ [kN]</td>
<td>7260</td>
<td>9656</td>
<td>8104</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>1.33</td>
<td>1.12</td>
</tr>
<tr>
<td>$F_{b,x,d}$ [kN]</td>
<td>2862 (q=3)</td>
<td>4950 (q=2)</td>
<td>4227 (q=2)</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>1.69</td>
<td>1.04</td>
</tr>
<tr>
<td>$F_{b,y,el}$ [kN]</td>
<td>6517</td>
<td>6873</td>
<td>7662</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>1.36</td>
<td>1.18</td>
</tr>
<tr>
<td>$F_{b,y,d}$ [kN]</td>
<td>2806 (q=3)</td>
<td>4623 (q=2)</td>
<td>3834 (q=2)</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>1.65</td>
<td>1.05</td>
</tr>
<tr>
<td>$u_x$ [cm]</td>
<td>0.95</td>
<td>1.68</td>
<td>1.70</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>1.77</td>
<td>1.79</td>
</tr>
<tr>
<td>$u_y$ [cm]</td>
<td>1.29</td>
<td>2.28</td>
<td>2.36</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>1.77</td>
<td>1.83</td>
</tr>
<tr>
<td>$u_3$ [cm]</td>
<td>/</td>
<td>3.80</td>
<td>7.26</td>
</tr>
<tr>
<td>Increase fac.</td>
<td>/</td>
<td>4.94</td>
<td>9.51</td>
</tr>
</tbody>
</table>

Results in Table 2 show that the increase of the base shear of the structure upgraded with the steel braced frame is less than in case of the other systems despite the higher additional mass. This is due to its lower rigidity and consequently higher period of vibration, which give lower values of accelerations in the response spectrum.

From comparison of results presented in Table 2 it can be seen that the increase of displacements at the top of the basic structure is higher when the upgrade structure is more flexible. This leads to the amplification of horizontal displacements at the top of the upgrade structure (“whip effect”). On the other hand, more rigid and stiff upper structure transfers higher seismic forces onto the lower one. In reality, the upgrade structure made of Xlam panels is more flexible due to semi rigid mechanical connections between the panels and anchors with nonlinear behaviour which was neglected in the linear dynamic analysis performed in this study. However, the amplified horizontal deformation with this type of upgrade structure is not problematic: Xlam construction is light but rigid, it softens after activation of mechanical fasteners, and it is able to dissipate energy, which transfers lower seismic forces onto the lower one. One of the important issues is that the mass of the upgrade is more uniformly distributed over the walls of the Xlam timber box.

Figure 5: Time history response of linear dynamic calculation for the upgraded structure with a) Xlam timber box, b) steel braced frames, and c) combined steel frame and Xlam timber panels

5 DESIGN CODE ISSUES

In Section 2, the possibilities of using simplified models have been discussed. The results were reasonable only when the existing structure was checked for the influence of upgrades. On the other hand, results for the upgrade structures were completely wrong if the self standing upper structure with ground acceleration input was analyzed because of incorrect boundary conditions. In EC8, any special guidelines related to upgrade structures cannot be found. Therefore, the combined structure has to be considered in seismic design as a whole and not analyzed separately for different construction parts.

As upgraded structures are mostly composed of different lower (heavy) and upper (light) construction systems, they are irregular in elevation. Therefore, modal analysis is required for seismic design. The main problem is the determination of the behaviour factor where the lowest value among the load-bearing subsystems has to be assigned to the entire structure.

In construction practice when there is an intention for upgrade of an existing building usually designers face the problem that they cannot pass and fulfill all Eurocode requirements because the building was designed according to some older regulations.
5.1 BEHAVIOR FACTOR

Eurocode 8 gives directions for determination of behaviour factor for different types of structures as a function of construction material, determination of structural system, and capability of energy dissipation but it does not give directions for combined structures. The question arises if it is possible to use different behaviour factors for existing and upgrade structures. In reality, every storey of the structure along the height of the building could dissipate energy according to its construction ability. Various reductions of seismic forces could be possible in any different construction system along the height of the building. When the deformation stage of upgraded structure is checked, the behaviour factor does not have any meaning in these displacement analyses and it is not taken into account.

In our case study, the lowest behaviour factor of the component subsystems was applied to the combined system as we were aware that this method gives conservative results.

6 CONCLUSIONS

Modal analysis and linear dynamic analysis were performed for the combined lower and upper structures of three types using the exact modelling and two simplified models in order to evaluate the influence of the upgrade on the existing RC building and to study the possibility of simplification of the earthquake analysis. It was found that the simplified models give good results for the existing base structure, while the upper part of the composed structure (upgrade structure) has to be designed using the exact full composed model because simplified models give completely wrong and unsafe results.

Table 3: The main characteristics of different upgrades

<table>
<thead>
<tr>
<th>Upgrade</th>
<th>Additional weight</th>
<th>Load transfer</th>
<th>Change in rigidity</th>
<th>Seismic forces increase</th>
<th>Whip effect</th>
<th>Speed of construction</th>
<th>Displacements in elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box Xlam timber panels</td>
<td>O</td>
<td>X</td>
<td></td>
<td>O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel braced frame</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid steel frame and Xlam panels</td>
<td></td>
<td></td>
<td></td>
<td>O</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend: ✓ - good/small problem, O - natural/normal problem, X - bad/big problem

It is important to limit the additional upgrade mass to keep the seismic forces in the range of the previous level on the existing building before the upgrade. Seismic forces depend also on the natural period of the structure and they are decreasing with increasing of the natural period of the structure. It depends on the composition of the system where rigidity and weight of the upper structure is of the major importance. If the upgrade structure is too flexible or if the difference between the rigidity of the lower and the upper structures is too big, the “whip effect” with amplified horizontal deformations at the top of upper structure could appear.

Regarding the Eurocode 8 requirements, it was pointed out that there is a gap in determination of behaviour factor without regulation for seismic design of upgraded or composed structures along elevation. Table 3 points out the main characteristics which should affect the decision of a type of upgrade structure.

ACKNOWLEDGEMENT

Dr. Bruno Dujč’s research work is partly financed by the European Union.

REFERENCES