EARTHQUAKE RESISTANCE OF TIMBER STRUCRUTRES

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ABSTRACT

The prime objective of this paper is to describe the basics of the seismic design of the timber constructions. The experience from North America and Japan shows that when designed properly wooden structures can resist extreme conditions like earthquakes. The ability of structures to develop plastic deformations without drastic reduction of strength and resistance is called ductility. The purpose of this paper is to present the ductile behavior of the timber structures in tree directions – material; element/joints; structure as a whole. Timber has orthotropic properties and although it behaves in ductile manner when loaded under compression, especially perpendicular to the grain, it is brittle under tension perpendicular to the grain. The connections in timber structures introduce a foundational aspect in terms of the seismic behavior of the construction, since they act as ductile valves and enable dissipation of energy. Due to its global ductility, the structure posses the ability to withstand deformations without developing high stress concentrations. Seismic resistance of timber structures is based on their advantages – a low-self load; ductile joints; in general very regular building layouts. The paper was done as a specialized literature survey and is based on the conceptions of the capacity seismic design and the system of structural Eurocode standards (EN 1995-1-2:2004 and EN 1998-1:2004).

Key words: seismic design, timber constructions, earthquakes

PREFACE

The soil movements induced by earthquakes produce vibrations in buildings and, thus, inertial forces in the structures. These forces are called seismic loads. During a seismic event in the foundations of the structures are induced kinematic actions with random properties. Each structure is a dynamic system with specific masses and stiffness and when its foundation moves it deforms not as a rigid body but develops additional movements, velocities and accelerations. If assumed that the inertial masses of a dynamic system are concentrated in single points, then the seismic loads induce inertial forces in these points proportional to the masses and the accelerations.

The most common seismic design approach is the spectrum modal response method for evaluation of the construction's response to a seismic action. This method is based on the dynamic characteristics of a structure regarding its linear and elastic behavior, but its ability for a hysteretic dissipation of the seismic energy is evaluated using reduction factor called *behavior factor q* in Eurocode 8.

Stiff and brittle structures usually do not perform well against seismic loads, since only a small deformation may cause failure. This evokes the necessity for structures to develop plastic strains under strong seismic events. These deformations may cost the construction local failures but this is a mechanism to dissipate part of the seismic energy. This property is called ductility of a construction. Ductility means good development of plastic strains and allowing the structure to adapt during extreme events using its ductile elements. Ductility should be considered on three bases – ductility of the material, of the elements and connections between them, and of the construction as a whole. Each construction is a combination of "brittle" and "ductile" elements. Unwanted forms of brittle failures could be avoided by providing the ductile elements with ability to fully deform plastically and as a result to dissipate the seismic energy. This is the basis of the conception for capacity seismic design, included in many national constructional standards, including Eurocode 8.

The regulations in Europe for the seismic design of timber constructions are provided by two harmonized standards – EN 1995-1-2:2004 – *Design of timber structures* (Eurocode 5) and EN 1998-1:2004 – *Design provision for earthquake resistance of structures* – Part 8 *Specific rules for timber buildings* (Eurocode 8).

1. BASIC CHARACTERISTICS OF THE TIMBER-BASED STRUCTURES REGARDING THEIR SEISMIC RESISTANCE

The safety of a structure for seismic events can be considered sufficient if the following conditions of resistance, ductility and equilibrium apply.

1.1. Timber as a ductile material

As well known, the wood may be described as an orthotropic material - it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential. Additionally variety of natural characteristics affect the mechanical properties of wood, such as moisture content, content of knots, etc.

Main strength axis is longitudinal - parallel to grain, whereas the radial and tangential which are „perpendicular" to the grain are substantially weaker. For example timber is extremely weak for „tension perpendicular the grain" stress condition. It should be avoided at all if possible, and mechanically reinforced if not.

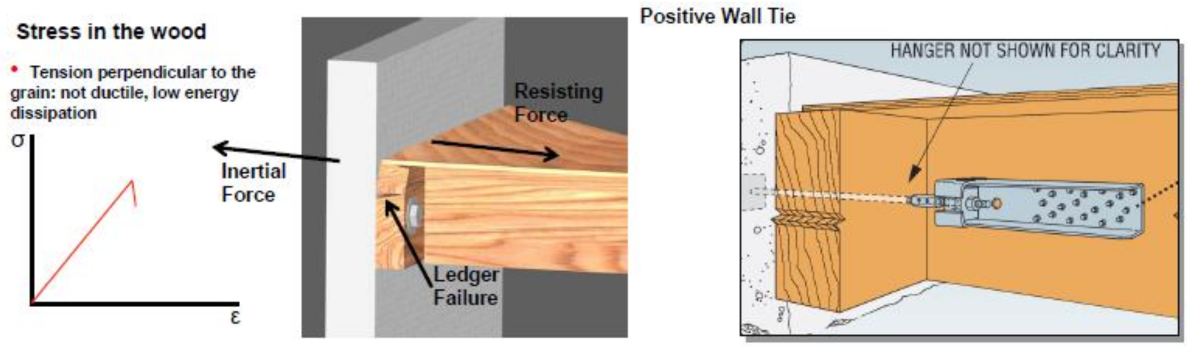

Figure 1: Stress condition "tension perpendicular to the grain" should be avoided

In contrast „compression perpendicular to grain" is the most ductile basic wood property and in such stress conditions the timber is capable of dissipating seismic energy.

1.2. Structural types according to Eurocode 8

As stated above, the behavior factor q for timber structures obtains the value between 1.5 and 5. Eurocode 8 gives the behavior factor q values for different structural types as below:

Table 1: Values of the load reducing behavior factor q for different timber construction types according to Eurocode 8

Type	q value	Description of the construction
A	1,5	*Structures having low capacity to dissipate energy such as*: cantilevers, beams, two or three pinned joint arches, trusses joint with connectors
B		*Structures having medium capacity to dissipate energy such as:*
	2,0	Glued wall panels with glued diaphragms, connected with nails and bolts, trusses with doweled and bolted joints, mixed structures with timber frame and non-load-bearing infill.
	2,5	Hyperstatic portal frames with doweled and bolted joints
C		*Structures having high capacity to dissipate energy such as:*
	3,0	Nailed wall panels with glued diaphragms, connected with nails and bolts, trusses with nailed joints.
	4,0	Hyperstatic portal frames with doweled and bolted joints.
	5,0	Nailed wall panels with nailed diaphragms, connected with nails and bolts.

If the building is non-regular in elevation the above q-values should be reduced by 20 %, but must not be lower than 1,5. To ensure the above classification of structures, the dissipative zones should be able to deform plastically for at least three fully reversed cycles.

In case the building is stabilized for lateral loads with different structural types in the two main directions, each one can be treated separately and a different behavior factor for the two directions may be applied.

1.3. Ductile elements of the timber based structures – their connections.

Timber has a low capacity to dissipate seismic energy, except under load condition „compression perpendicular to the grain“. So the behavior of the whole timber structure during seismic events depends on the ductility of its connections. To avoid an unacceptable strength loss in cyclic loading, three general principles should be followed. Details should be designed so that the elements cannot easily pull out, brittle material failures should be avoided and it should be used materials which retain their mechanical properties during cyclic loading. Mechanical joints in timber structures usually perform in a semi-rigid manner and plastic strains may develop, if the fastener spacing and the end distances are according to the design rules. This way joints are able to dissipate the seismic energy.

Ductility of the connections could be determined by their force-deformation curve. The force-deformation loops are usually quite narrow, whether the deformations are low or high. In well designed joints the seismic energy is dissipated through embedment of the wood and through plastic deformations of the mechanical connector. The energy dissipated in a half cycle through plastic strains in the non-linear zone is measured as the shaded E_d area shown in the figure below. The ratio between the dissipated energy and the potential energy E_p is called the hysteresis equivalent viscous damping ratio v_{eq}. The values of v_{eq} are more or less constant. For well-designed connections between plywood and the timber frame in shear walls this ratio is about 8 – 10 %.

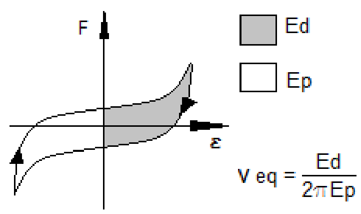

Figure 2: Typical "load – deformation" curve of mechanical joint in timber structure under cyclic loading. Dissipation of energy in a loading cycle.

In order to avoid splitting of wood and brittle failures, Eurocode 5 states the minimum end and side and spacing distances of the fasteners and these should be obeyed. They are given to ensure that the connection failure is not brittle. Splitting may also be prevented by using reinforcing materials in the connection areas, which give higher tension strength in the direction perpendicular to the grain of the wood. Such reinforcing materials are, for example, plywood panels and densified veneers. In addition to preventing the wood from splitting, the reinforcement ensures the yielding of the fasteners and thus enhancing connection ductility. To ensure the dissipation of energy, it is possible to take advantage of the slenderness of the fastener. The slenderness is defined as the ratio between the wood member thickness and the fastener diameter. Fasteners with high slenderness ratios dissipate more energy since the plastic yield points are, in this case, always formed in the fastener. In addition, the wood splitting may be prevented by increasing the member thickness in comparison to the fastener diameter. Mechanical connections are not usually sensitive to fatigue failure, although there are some exceptions. As an example, there are several types of steel plates with punched teeth, where the failure may occur as a pull-out of the teeth or brittle failure of the steel plate.

2. SEISMIC RESISTANCE OF SOME OF THE MOST POPULAR TIMBER-BASED STRUCTURAL SYSTEMS

2.1. Light frame structres with shear walls

Eurocode 8 gives rules for the seismic design of timber constructions of *light frame and shear walls.* According to Eurocode 8 classification of the construction types, this particular one has the highest behavior factor q=5,0. The main aspects of the seismic design of these structures are the construction of the shear walls, of the floor diaphragms, of the joints and anchorage of the buildings.

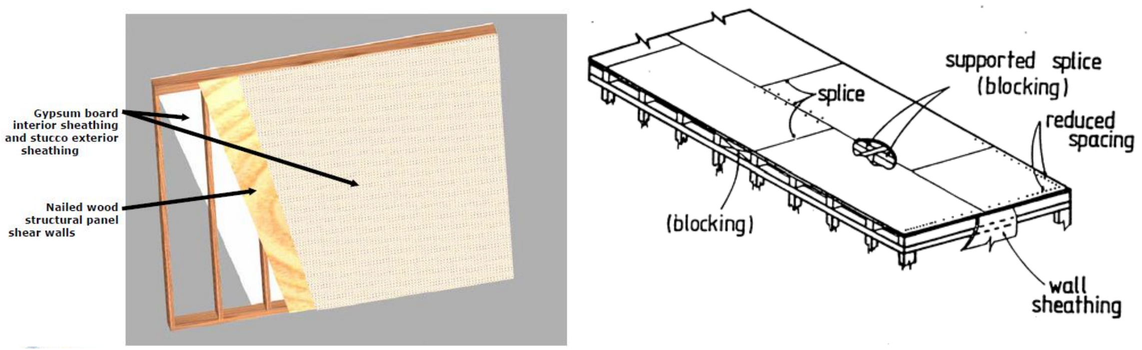

Figure 3: Example of a shear wall and floor construction

2.1.1. Shear walls

In this structural system the lateral stability is effectively provided by the use of shear walls with panel sheathing. The timber frame of the wall bears the lateral loads which are equally distributed due to the sheathing panels. Usually shear walls consist of vertical struts, equally spaced, which are connected to top and bottom plates. To this frame, a sheathing panel is attached by nails or screws, on one or both sides of the frame. Wood-based boards, plywood or OSB are often used as the sheathing panel. Gypsum boards may also be used. According to Eurocode 5, the shear capacity of the shear wall is based on the shear capacity of the fasteners. It's assumed that the shear force is equally distributed between the fasteners. The struts of the frame are designed for compression and tension forces for which later are designed also the anchorage connections. The end struts of shear walls, as well as the bottom plate, should be anchored to the foundations to resist uplift and sliding forces. In a multi-storey house these anchoring forces should be considered from storey to storey as these accumulate towards the bottom storeys.

2.1.2. Floor diaphragms

The distribution of lateral loads to several shear walls depends on the rigidity of the floor and the rigidity of the shear wall. The floor diaphragms as well as the shear walls must be designed for lateral loads according to the rules given in Eurocode 5 with some exceptions given in Eurocode 8.

2.1.3. Anchorage of the building

In order to transfer the lateral loads to the foundations, the building has to be anchored to the storey below and then on to the foundations. Anchoring is normally required at the ends of shear walls to account for the uplift forces (due to overturning when the building's selfweight does not compensate for the effects of the lateral load) and at the bottom plate to account for the sliding (slip from base shear). The uplift and sliding forces are anchored independently of each other with special connectors.

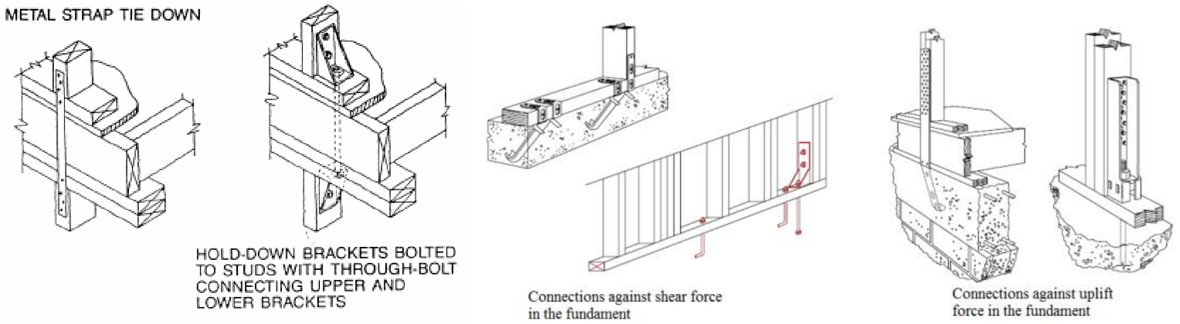

Figure 5: Anchorage connections

2.2. Construction of highly subdivided light timber frames with masonry infill.

Some traditional timber structures have gained popularity of seismic resistant constructions throughout the centuries. For example, an ancient traditional building system of timber houses resisted a catastrophic earthquake with magnitude of 7,6 in Kashmir, October 2005 while millions of modern buildings were destroyed. This provoked a team of two universities to study this ancient construction system and to publish free manual as a valuable reference for future constructions. In this way the revived structural system was used for rebuilding of over 120 000 homes for the local population in less than 3 years.

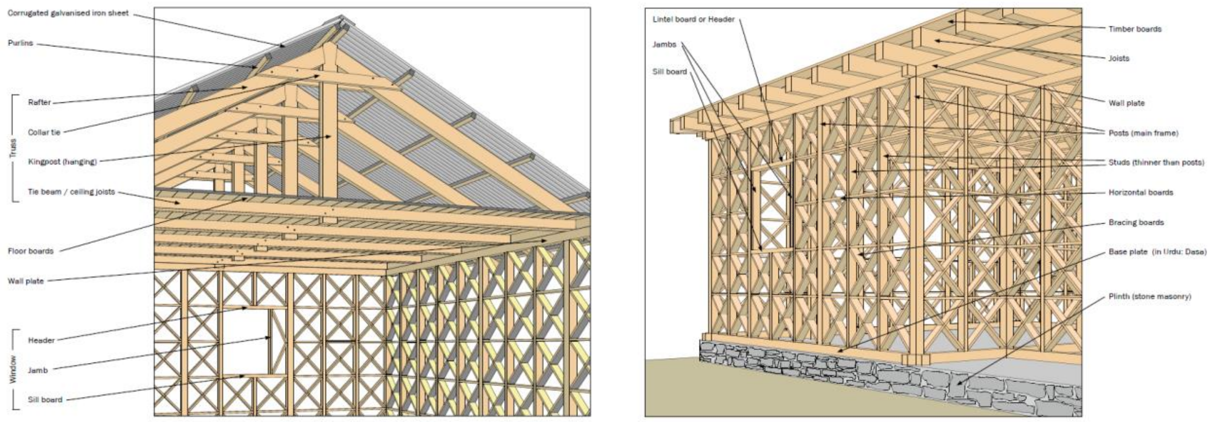

Figure 6: Construction system Dhaji traditional for the Kashmir region

The main constructional principles of this building system are as follow:

- Choice of suitable field for building;
- Regularity in plan and elevation of the building; Minimized number and sizes of the openings in the walls;
- Strength of the main construction elements – wall frames, floor and roof structures, foundation; Secure infill of the wall frames;
- Strength and ductility of the joints, secure anchorage;
- Preserving the timber from water, insects, fungi.

2.3. Timber log constructions

Another traditional system for building with timber is the *Log* construction system. Specifically this structural system is able to resist lateral loads like wind or earthquake, due to the corner interlocking joineries and the friction between the logs.

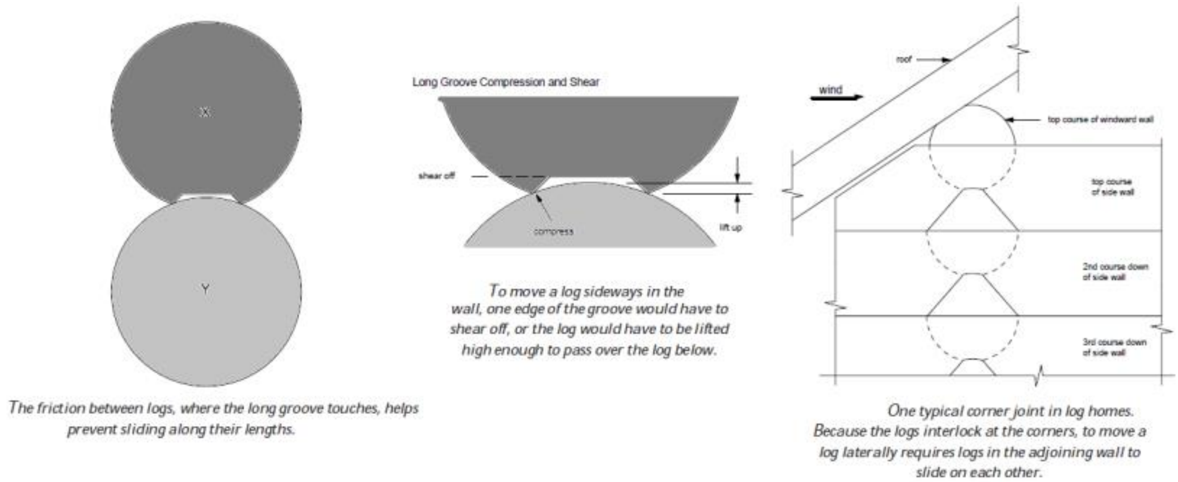

Figure 7: The joineries between logs are providing the lateral stability of the building

The building must be adequately secured to the foundation by through-bolts connecting the top course of the logs to the foundation. Then the corner interlocking joineries of the logs distribute the lateral loads equally between the walls as well as they prevent horizontal movements and uplift of logs. Meanwhile the friction forces that are induced in the long grooves between the logs help transfer of lateral loads from the top log to the foundation of the wall. In fact, these log joineries help dissipate the seismic energy so the log building will resist strong earthquakes.

2.4. XLam Buildings

In the recent years XLam structures (XLam is cross-laminated timber boards) are becoming wide spread in Europe among the timber-based constructive systems, even for multi-storey buildings. However considering the seismic behavior of this type of structures, very few research programs have been carried out up to now and none of them including a shaking table test on a full-scale specimen. This resulted in a lack of harmonized set of products, design, erection, inspection and maintenance rules in the European Standards for this constructive system. However a test of a three-storey XLam building with sizes in plan 7x7 m and overall height of 10 m was performed in a Japan laboratory. The building was installed on a steel frame platform with anchorage bolts and steel angles connectors. The test was performed with the seismic records of 15 world catastrophic earthquakes. The results showed that the construction resisted without any serious and yet repairable damages.

Record	Code	PGA [g]	Restoring intervention (before the test)	Observed damage (after the test)
Nocera Umbra	06070510	0.50	Tightening of holdown anchor bolts Replacing of screws in vertical joints between panel	None
El Centro	06070515	0.50	Tightening of holdown anchor bolts.	None
Kobe	06070714	0.50	Tightening of holdown anchor bolts Replacing of screws in vertical joints between panel	None
Kobe	06070709	0.80	Idem	Slight deformation of screws in vertical joints between panels
Kobe	06070714	0.50	Idem	None
Kobe	06070719	0.50	Tightening of holdown anchor bolts	None
Kobe	06071006	0.80	Replacing of holdown anchors and tightening of bolts. Replacing of screws in vertical joints between panel	Slight deformation of screws in vertical joints between panels
Nocera Umbra	06071009	1.20	Tightening of holdown anchor bolts. Replacing of screws in vertical joints between panel	**Holdown failure** and deformation of screws in vertical joints between panels

Figure 8: Test of XLam building on a shaking table and summary of the test results

3. SUMMARY

The rich experience of building with timber around the world shows that any of the timber – based construction system is ecological and economical but yet resistant to earthquakes when the structure is designed and built according to the regulations in the standards for building in seismic regions. Considering wood as an ecological, renewable, technological material, it is clear that building timber – based structures is sustainable process both in technical and social-economical aspect.

REFERENCES

1. Belev, B. 2002. Seismic Design of Steel Structures, UACEG
2. EN 1995-1-2:2004 – Design of timber structures.
3. EN 1998-1:2004 – Design provision for earthquake resistance of structures – Part 8 Specific rules for timber buildings.
4. FEMA. 2004. Design Examples of Timber Structures 13-1, Instructional Material
5. Toratti, T. 2006. Design guidance on Eurocode 8 for practicing engineers for timber structures. International Workshop on „Earthquake Engineering on Timber Structures“, Coimbra, Portugal
6. Ceccotti, A. Follesa, M, 2006. Seismic Behaviour of Multi-Storey XLam Buildings, International Workshop on „Earthquake Engineering on Timber Structures“, Coimbra, Portugal
7. Hahney, T. 2000. How Log Houses resist lateral loads. Canadian Log Builders Association
8. Schacher,T., Ali, Qaisar. 2009. DHAJI CONSTRUCTION For one and two storey earthquake resistant houses – A guidebook for technicians and artisans, University of Engineering and Technology, Peshawar, Pakistan