Current requirements in buildings regulations and codes - EN 1998-1

EN 1998-1 covers the design requirements for earthquake resistance for all structural materials.

Most earthquake design codes provide an acceleration response spectrum curve that specifies the design acceleration (which means the horizontal load) based on the natural period of the structure. The basic principle of EN 1998-1 is that when the structure presents a ductile behavior, the design acceleration and the horizontal force imposed to the building is reduced by division by the so called behavior factor q.

Timber is generally considered to be a good structural material for construction in seismic areas due its light weight and reasonable strength in tension and in compression. The good seismic performance of wood is reflected by its strength/mass range similar to structural steel [35-55]. However, a) timber elements do not present large deformational ductility; b) response of timber elements up to failure is approximately linear elastic; c) collapse is sudden, mostly associated with defects inherent to the natural origin of timber.

In view of the limited ability of timber to behave nonlinearly, energy dissipation should be mostly in connections and timber elements should respond linearly. Some, little, nonlinear behaviour can be expected in compression perpendicular to the grain but, tension perpendicular to grain is markedly brittle.

Distinction between dissipative and low-dissipative structures depends mostly on connections nature. Semi-rigid and rigid connections are associated with this distinction, respectively. Dissipation of energy in connections has two main sources: a) cyclic yielding of metallic (normally steel) dowel type fasteners of the connections (nails, staples, screws, dowels or bolts) and b) crushing of the wood fibres bearing against the dowel. The first mechanism tends to be stable and provides large hysteretic cycles while the second causes thin hysteretic loops with significant degradation, due to the cavity being formed in front of the dowel.

Eurocode 8 proposes a classification of timber structures in Ductility Class Medium (DCM) and Ductility Class High (DCH) for dissipative structures and Ductility Class Low (DCL) in the case of non-dissipative structures. The choice of the Ductility Classes (DCs) is left to the designer but National Authorities may limit the use of the various DCs.

For timber structures the parameters that influence its ductility classification are the structural type (essentially reflecting the greater or lesser redundancy of the structure as a whole) and the nature of the structural connections (essentially reflecting its ductility and energy dissipation capacity). For the latter, EN 1998-1 states, in general, that properties of the dissipative zones (i.e. the connections) should be determined by tests, in accordance with EN 12512. However, for the most common connection types, some deemed to satisfy rules are presented in the code, in order to reduce the burden of testing connections in ordinary design situations.

It should be noted that for timber structures of DCL, the behaviour factor may be taken up to q = 1.5. Even tough, as indicated above, for this ductility class no significant decrease of the earthquake force is expected on account of a non-linear response; the use of a behaviour factor slightly greater that q = 1 is justified by the overstrength that timber structures normally present under earthquake action.

Materials and properties of dissipative zones

In general, the requirements for wood materials set out in EN 1995-1-1 also apply in the design of earthquake-resistant timber structures covered by EN 1998-1. However, in order to ensure the required dissipative behaviour in timber structures of DCM and DCH, some additional requirements have to be fulfilled with regard to the mechanical characteristics of the materials and to the characteristics of joints. In all cases, the objective of the additional requirements is to avoid brittle failures and to obtain connections with stable behaviour under large deformation reversals.

For connections in framed systems, specific conditions are set, besides the general reference to the need to demonstrate by testing that the connections have a stable low-cycle fatigue response and the explicit indication that glued joints may not be considered as dissipative zones (since they respond elastically up to failure which is essentially brittle due to debonding). In contrast, for sheating materials some minimum mechanical characteristics are required, namely:

- for particle-board panels the density should be at least 650 kg/m^3;
- for particle-board and fibre-board sheating the thickness should be at least 13 mm;
- for plywood sheating the thickness should be at least 9 mm.

This is intended to ensure the excellent ductile behaviour shown by nailed shear panel systems, which is usually superior to conventional diagonal bracing but relies very much on the properties of the sheating boards (Ceccotti and Touliatos, 1995). Also important for the appropriate response of this short of system is the avoidance of the pull-out of the nails under transverse cycling. To this end, a point side penetration of 6-8 times the sheating thickness is appropriate, and smooth nails should be avoided or be provided with additional provision against withdrawal (e.g.by coating or clenching).

Ductility classes and behaviour factors

For timber structures, EN 1998-1 presents upper limit values of the behaviour factor depending on the ductility class and the type of structure and connections used.

Table 1 – Maximum values of the behaviour factor q for timber structures of DCM and DCH

Structural type	DCM	DCH
Wall panels with glued diaphragms connected with nails and bolts	Glued panels $q = 2.0$	Nailed panels $q = 3.0$
Wall panels with nailed diaphragms connected with nails and bolts	-	Nailed panels $q = 5.0$ $(q = 4.0)$
Trusses	Doweled and bolted joints $q = 2.0$	Nailed joints $q = 3.0$
Mixed structures with timber framing and non-load-bearing infills	$q = 2.0$	-
Hyperstatic portal frame with doweled and bolted joints	$\mu \geq 4$ $q = 2.5$	$\mu \geq 6$ $q = 4.0$ $(q = 2.5)$

Besides the general upper limit of q = 1.5 for DCL accounting for overstrength, for DCM and DCH the values indicated for q in Table 8.1 of EN 1998-1 are reproduced in Table 1 with a different arrangement that highlights the influence of the various parameters on the ductility of timber structures (namely the superior behaviour of correctly designed and executed nailed connections).

The values presented in Table 1 are appropriate for buildings, which are regular in elevation. For buildings with non-regular structure in elevation, the behaviour factor should be reduced 20%, as is also required for buildings of other structural materials, in order to account for the expected higher load ductility demands in those cases.

The values presented in Table 1 are applicable if the dissipative zones in the structure are able to withstand, without a decrease of strength of more than 20%, three fully reversed cycles at a ductility demand of $\mu = 4$ for DCM and $\mu = 6$ for DCH. For portal frames the ductility should be evaluated in terms of the rotational capacity of the joints, whereas in wall panels the ductility should be evaluated in terms of shear displacements of the panels.

In principle, the available ductility should be measured by testing. For non-bilinear responses (i.e a response without a clear identification of the yielding point), as is normally the case for timber joints with doweled metal connectors, it is sometimes difficult to evaluate the available ductility, due to the absence of a precise value for the yielding displacement (or rotation). To overcome this difficulty, a bi-linear diagram enveloping the real constitutive diagram may be used as an equivalent response, in which case the yielding is defined precisely. It is suggested (Ceccotti, 1995) that for timber structures the second branch of such an equivalent bi-linear envelope has a stiffness which is one-sixth of the stiffness of the initial (linear) branch.

This requirement of testing would be very cumbersome in most ordinary design cases, and so the following deemed to satisfy rules are given in EN 1998-1:

1. The slenderness of the fasteners in doweled, bolted and nailed connections should be greater than 10 ($t/d \geq 10$, with t being the thickness of the connected member and d the fastener diameter) and the fastener diameter should not be larger than 12 mm;
2. The sheating material (wood based) in shear walls and floor diaphragms should have a thickness larger than four times the fastener diameter ($t \geq 4d$), and the nail diameter should not exceed 3.1 mm.

These requirements reflect that, for good performance of the connections under cyclic load, thick timber and slender dowels are preferable because they allow for yielding in bending of the fasteners (whereas with stocky dowels the failure mode will mostly be associated with the crushing and splitting of the timber fibres, which does not allow for the dissipation of energy).

I n any case, the numerical values are relatively severe, and it has been suggested (Ceccotti and Touliatos, 1995) that an even less demanding value of $t/d \geq 8$ is still very much on the safe side in terms of the ductility of connections. Also it is worth mentioning in this context that EN 1995-1-1 allows much larger bolts and dowels with diameters up to 30 mm (clauses 8.5.1.1 and 8.6 of EN 1995-1-1).

Hence, when the above requirements are not met strictly (i.e. $t/d \geq 8$ and $t \geq 3d$, respectively, for cases 1 and 2 above) it is still permitted to avoid testing of the connections of dissipative structures, but the maximum values of the behaviour factor should be decreased as shown in parentheses in Table 1.

For structures having different and independent properties in the two horizontal directions, the q factors to be used for the calculation of the seismic action effects in each main direction should correspond to the properties of the structural system in that direction and can be different.

Detailing

For buildings of DCM and DCH, additional detailing rules are required in comparison with the general provisions of EN 1995-1-1. These additional rules intended to enhance the behaviour of connections and horizontal diaphragms.

For bolts, an absolute limit of 16 mm is established for their diameter, unless toothed ring connectors are also used. These provide some confinement of the wood in front of the bolts and allow for the larger bearing forces associated with larger bolts. Furthermore, it is required that in pre-drilled connections they are tightly fitted. This is because oversized holes may cause a non-uniform distribution of loads in different bolts of the same connection. In such cases there may be a tendency to overload some bolts,, which triggers premature splitting and crushing of the wood against these bolts, initiating a chain collapse in the other bolts.
For floor diaphragms, the additional detailing provisions are intended to increase the effectiveness of the sheating material and the stability of its connections (particularly at the edges of the panels) to the framing timber elements. This is reflected by forbidding consideration of the increased resistance of edge fasteners (allowed for in general terms for "non-seismic/non-ductile" cases by clause 9.2.3.1. of EN 1995-1-1) and by more

strictly controlling (i.e. limiting) the nail spacing at the panel edges allowed by clause 9.2.3.2 of EN 1995-1-1.

Also closer spacing has to be adopted for fasteners in areas of discontinuity in case of relatively high seismicity ($a_gS \geq 0.2g$) to avoid the premature initiation of rupture in those areas and to somehow compensate for its decreased stiffness. In any case, the minimum spacing established in EN 1995-1-1 (clause 10.8.1) should always be respected to ensure that splitting of the wood is prevented. Accordingly, in these areas of discontinuity, the dimensions of the timber elements should be generous to allow effective nailing that is not too closely spaced.

Safety verifications

Safety verifications are to be made using the general resistance models provided in Sections 5 and 6 of EN 1995-1-1. Naturally, in the seismic design situation, the strength modification factor k_{mod}, which accounts for the influence of the duration of the load (and also of the moisture content) on the resistance of timber or wood-based materials, should be taken with the value appropriate for instantaneous actions (see Table 3.1 of EN 1995-1-1).

Regarding the partial factor for material properties γ_M to be used in the ultimate limit state verifications, an important distinction is made between: a) structures of DCL, for which the γ_M values for the fundamental load combinations are recommended, and b) structures of DCM or DCH, for which it is permitted to use the smaller (equal to 1.0) values are recommended for the accidental load combinations (see Table 2.3 of EN 1995-1-1). This is an important departure from analogous recommendations in other sections of EN 1998-1 for other structural materials (namely Section 5 for reinforced concrete, Section 6 for steel and Section 7 for composite), in which it is recommended that γ_M values for the fundamental load combinations are used in the seismic design situations. This rule has an important influence on the outcome of the design for the two types of structure (low dissipative and dissipative), and reflects the more reliable response of timber connections and timber structures satisfying the additional requirements for dissipative structures which are set forth in this section of EN 1998-1.

Ceccotti, A. and Touliatos, P. (1995) *Detailing of Timber Structures in Seismic Areas. Step lecture D10, STEP/Eurofortech – Timber Engineering*, Vol. II. Centrum Hout, Almere.

Ceccotti, A. (1995) Timber Connections Under Seismic Sctions, STEP lecture C17 *STEP/Eurofortech – Timber Engineering*, Vol. II. Centrum Hout, Almere.

EN 12512: 2001, *Timber structures - Test methods – Cyclic testing of joints made with mechanical fasteners*, CEN, 2001, Brussels, Belgium.