Mechanical Failures of the Timber Structural Systems

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1. Foreword

The stability of the existing timber structures is commonly studied with the general methodology of the Engineering Science, the Theory of Construction, the Theory of Materials applied to the wood, the Technology of the Timber Constructions (see for instance the European Codes). Whilst detailed studies can be found for deformation, rupture, collapse of members or small samples of clear wood and solid timber in structural size, only a few specialized publications deal with structures for the same problems.

The most common causes of failure of the timber structural systems are inadequacy of configuration (geometry of the structure, sizing of the members, kind of connection of the members, bracing etc.) in relation to the actions, both static and dynamic loading; besides slenderness, instability, ..., defects of the wood laid in place, severe biotic damages, accidental factors.

No doubt that the decay of the wood caused by beetles and fungi is a major problem both for members and structures too, especially in the tropical countries; in fact mechanical failures can also be caused by biotic factors that reduce the strength of the material as to the designed actions, thus reducing or cancelling their efficiency and safety.

The failures can hit the structure at any hierarchic level, i.e. that of the members, the units, the whole structural system and the connections.

The widespread habit of replacement of the damaged parts of the ancient structures or their total demolition and rebuilding is, unfortunately, extended up to the present days though only by a restricted number of culturally unacquainted operators who rely on a supposed tradition. This habit has the effectual alternative, required by the contemporary cultural instances, of the repair and strengthening with minimum disturbance of the ancient complex.

This new vision demands for an updated scientific and technical approach. If repair and strengthening must be planned in order to recover the lost efficacy of the system and, at the same time, avoid modifications or at least minimize them, in any case without significantly altering the general concept of the same system, the mechanical failures as well as the causes of their presence must be known and interpreted; a general evaluation of the efficiency and of the safety of the system will then be possible.

Planning the strengthening will subsequently follow in a natural way as the activity meant to take the right measures and put in place only those remedies judged adequate to counteract the recorded effects of each failure, avoiding the assumption of the generic remedies featured and recommended in the handbooks and in the dépliants of companies without a specific reference to the real nature of the damage, and cancel or at least neutralize the causes that are responsible of the problem.

The author wants also to stress out that this kind of comprehensive approach and this widening of the field of appraisal will lead to a deeper understanding of the existing
structures extended to all the components and including their behaviour, this way allowing a wider appreciation of the specimens which reached safely the present days or those disappeared or simply described in reports and treatises. Furthermore, the study of every unsuccessful outcome is, beyond any doubt, very fruitful for the conception of new systems and the design of new structures in the sense that it allows direct corrections and changes of trend: if one looks at the history of engineering, he discovers that it is what really happened. A different consideration of the whole process of the treatment of the existing structures will start the passage from the appraisal of the building material to that of the structures, from the concern for single elements to the consideration of a rational combination of components that are connected by relations the nature of which is either material or immaterial. This updated, enlarged attitude marks a significant achievement.

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The structural systems are, in general, designed as a combination of different elements; the basic ones are the Members that are organized and connected in a way to define Units of different kinds (frames, trusses, floors,……); a series of Units, connected and stabilized by auxiliary Members, determine the System; hence their organization is of hierarchic type.

All the components are arranged in such a way as to allow the ensemble to assume a configuration capable to withstand the actions (loads, settlements of the construction, dimensional variations caused by hygro-thermal fluctuations, …….) more or less cooperating to stiffness, strength and inhibition of motion of the adjacent parts.

Connections and joints, being designed according to various conceptions and ways of working, more or less engaging, more or less limiting the movements of the concurring members or units, can be seen as relations (see before) started between the various levels of components.

Significant examples of complex structural units are the floors, generally woven with principal beams, extended from one long wall to the opposite, which support a row (if any) of secondary beams placed in the orthogonal sense, thus forming a net so close to allow the placement of a co-operating boarding. The hierarchical conception is well expressed, amongst other matters, by the different size of the members, with a constant decrease in the ratio of the diminution of span and bay: for instance, the diminution from principal to secondary beams. Connections are usually made with the aid of nails.

Important and widespread examples of structural systems are the traditional roofs of the buildings, specially those of the Christian churches, which also fulfil a symbolic role: there the roof carpentries are in a way, with their hierarchical and specialized organization, expression of the ecclesial system, conceived in the same way.

The lead sheets covering of the St Catharine church in the Sinai, Egypt, rests on a roof of the VI c. composed by a series of trusses, the earliest known, with king post and struts, surmounted by purlins, joists etc. The rafters are connected to the chord by deep joints of the type tenon-mortise. The king post is fully perforated at the upper end so as to allow the insertion of the tenon-shaped extremity of the rafters.

The *cotto* (earth ware tiles) covering of the St. Mark’s church in Florence rests on a series (built in the XIV c.; two of them were built in the following century.) of traditional king post timber trusses, composed by members connected by traditional joints and iron fittings. The trusses are connected to each other by purlins (the auxiliary members) and joists which provide stability in the vertical plane to each unit and reduce the mesh to the size of a large and thin brick (*pianella*). The front and back pediments of the building provide stability to the series of units as well. The appropriate grading of the sizing of each member, from the massive chords and rafters of the trusses, passing trough the purlins and joists of medium size to the thin struts and the small rulers of the upper texture, ensures each role being pursued efficiently and the structural system equilibrated.

The system is resistant to the static and dynamic actions, steady and balanced. The St Mark’s roofing, a simplified and standardized product of the tradition, is similar to
hundreds of timber roofs in Italy and Near East. A few minor failures hit the roof of St Mark’s building over the time but it arrived safe and genuine to our consideration until the rough and destructive replacements operated a few years ago by the Authority responsible for the preservation of the Florentine Monuments.
The late gothic roof of the Cathedral of Nicosia, Sicily (De Francisco, Tampone, Copani, Funis etc.), is made in a much more complicate way but one can recognize the application of the same structural concept.

2. Objectives

Main purpose of the present paper is to present a set, systematic though abridged and simplified, of the most frequent failures of mechanical nature that occur to timber structures. The situations presented here are extreme but it is possible to distinguish different levels: failure as reduction of serviceability or safety, presence of cracks, breaking, collapse. In any case all the cited phases are preceded by peculiar symptoms.

Doing so the author intends to contribute to the building up of a systematic atlas of failures, the frequent and the rare ones, to help in the appraisal methodology of the mechanical characteristics and behaviour of the ancient timber structures. The study itself has its own strong appeal but we ought to remember that it is essential as a preliminary research for the assumption of the measures of collapse prevention and strengthening.

3. Failures of the members

Members, especially the beams stressed by bending, that are not attacked by fungi and beetles, break with the crack of single fibres, therefore with a grinding and in a progression. Decayed members break more easily than healthy ones, with a neat and sudden crack; the time of the event is unpredictable.

Due to the fibrous nature of the wood tissue, the way of breaking of the members is influenced by the kind of stress.

(For a description of the most recurrent types of member, their names, role etc., and of the causes and kind of their decay and failure, see Tampone, 1996, cit., and UNINormal....)

3.1 Compression

The longitudinal compression stress mainly occurs in pillars, columns, posts, stakes, in rulers of the lattice girders etc.; in a king post truss the struts are compressed (see over), the rafters are subjected to bending and compression.

The peculiar way of deforming, and therefore the typical failures in general, of the wooden pieces subjected to compression has been well explained by Curioni (Turin, 1885), Giordano (Milan, 1993, 2001, ...), Wille (Oldenburg, 1950) (Figures 1,2,3,4).

The failures are transversal lines which represent the crumpling and buckling of the cells, generally visible to the unaided eye, sometimes to be looked for with optical aids. When occurring at one end of the member, the base or the regions close to it can undergo a general swelling of the wood with longitudinal fissures; when occurring at the base of the piece, the enlargement of the bottom sections produces fissures which are the effect of splitting.

The failures to transversal compression, to which wood is much weaker, are featured (F. Wille, cit.) by depression of the compressed area, permanent if the stress is adequate, and of a large surrounding region with bulging of the cross section if this is narrow (see figure 2).
**Figure 1.** Deformation and break of longitudinally compressed pieces of wood according to the position in the shaft and the dimensions (Curioni)

**Figure 2.** Shape of the rupture lines of timbers containing the medullar axis, longitudinally loaded (from Giordano, cit.)
Figure 3. Wille, F., cit. Deformation of a wood member compressed in the transversal direction

Figure 4. Impression of a scaffolding base on a lying board (Tampone, 2007)
Slender compressed elements can undergo instability by point loading. The struts of the lattice girders and the struts of the king post (Figure 5, trusses of the Church of Mirteto, Italy) or of the composite Palladian trusses, if too thin, show this kind of failure. The consequences are generally severe on the member and on the whole structural system with regrettable consequences on the construction: the simple deflection of the strut, slender and therefore flexible, is sufficient to reduce the tension and avoid rupture in the member but the rafter experiences a further deformation and at last it breaks.

Figure 5. Church of Mirteto, Italy. Break of the rafter of a truss caused by the instability of the strut, with the complicity of a knot of the rafter and the notch for the joint, both exactly at the connection with the strut; this, too thin, is bent with the concavity towards the tie. The bending of the strut has been most probably preceded by the deformation of the rafter. The efficient connection of the rafter to the post is the cause of the bending of the post.

3.2 Tension

Almost pure longitudinal tension occurs in the pulled members of the lattice girders. The ties of the trusses are solicited by tension and bending due to their own weight. Very peculiar and interesting the special ties used to connect the opposite longitudinal walls in the architecture of the late Byzantine period all over the Oriental Roman Empire, in the Italian Venetian region as well, of the gothic churches in Europe and of the Islamic mosques. They are generally put at the top of the capitals or in the arches supported by columns, to prevent the rotation of the same walls caused by differential soil settlements or other situations critical for the stability; sometimes the transversal set is completed by longitudinal similar elements to configure a two-dimensions system.

The Hagia Sofia Basilica in Constantinople had similar ties; today only some stumps of them remain, after their replacement (first half of the XIX c., brothers Fossati) with bronze or iron elements.

The gothic church of Santa Maria dei Frari in Venice offers a splendid example of a spatial system of wooden ties, associated to the masonry structural system and integrated with it by an aesthetic point of view because they contribute to define the
spatiality of the three naves at the interior of the religious building. They are finely decorated with carvings.

The failure to longitudinal tension should lead to a progressive rupture of the fibres, not necessarily positioned in the same transversal section, at an accelerated pace because the section gets smaller and smaller. But it is very difficult indeed to take hold of the extremities of the member in a totally efficient way and what generally happens is that the material gives way at the abutment of the joint and the tension (the efficacy as well) vanishes.

A quite specific failure mode is to be considered the longitudinal break of the extremity of a member where a pin or nail is inserted in order to apply the tension: the wood divides along the fibres, in other words it splits, and the holding device slides along the borders of the split thus allowing the tension to release. (Figure 6)

**Figure 6.** Erroneous application of a screw with an electrically powered screwdriver, too close to the edges of a board. The board split

**Figure 7.** Gallery of the Academy, Florence (end of the XVIII c.). Deformation of the iron strip connecting the beam of the floor to the masonry, sliding of the clog with cut of the wood, caused by deformation and rotation of the beam under the loads

Typically, this situation is shown by the example of the beam of the end of the XVIII century of the (Figure 7 Accademia di Belle Arti in Florence) the nail and the hook
which ensure the iron device to the member cut the wood deeply for a length of 6 cm c. along the grain when the beam, due to the loads and the moment, was bent and tended.

In the practice a break to tensile stress is rare in the ties unless these are damaged by fungal attacks; mostly this kind of failure should be found in the beams. The best example the author knows, and the most recurrent indeed, of a failure that extends its influence far beyond the affected member, i.e. to connection, unit and system, is, in a truss, the break to tangential stress of the part of the chord which is enclosed by the end of the member and the indentation for the connection with the rafter; the notched indentation, sometimes completed with tenon and mortise plus an iron collar, is a device meant to prevent the rafter from sliding outwards pushed by the loads, in other words designed to absorb the thrust. The failure starts when the horizontal component of the compression conveyed by the rafter along its axis, to be considered longitudinal but applied to the margin of the member therefore a tangential compression, overcomes the strength of the material.
The failure is characterized by the longitudinal sliding of the interested part of the chord and, of course, of the lower and upper extremities of the rafter, respectively in the directions horizontal, outwards, and vertical, downwards.
The frequency of this failure is definitely influenced by the insufficient length of the piece, presence of defects of the wood and biotic attacks, especially fungal (see over). It has plenty of consequences as it will be seen in the paragraphs of the failures of connections, units, structural system.
More rare and less dangerous is the failure of the lower extremity of the rafter due to the same factors because the tension is fainter.

3.3 Bending

Predominantly, breaks of the members are caused by bending moments.
Several studies are available on the process and on the phases of decay and crack. After a first phase of deformation, the break generally occurs to tension at the intrados caused by the presence of knots and possibly other defects or damages (made by insects, fungi, wrong working etc.). (Figure 8). But rather often a complex phenomenon occurs if the wood is green or if the lower part of the beam is clear from defects and resistant, when the tensions induced by loading are bigger than the rupture strength to compression but, at the same time, lower than to tension: it is constituted by a first phase of bulging and longitudinal cracking of the compressed regions at the extrados followed by the increase of the tensile strain and consequently the crack at the intrados due to tension (Figures 9, 10).

![Figure 8. Diagram of the behaviour of the wooden beam subjected to bending](image)
The crack is generally characterized by the fact that the line(s) of rupture crosses the intrados edge of the member, not necessarily with straight breaking edges because its form can be influenced by specific factors such as irregular squaring, position of the member in the shaft, peculiarities of the grain and defects (mainly knots) or decay of the wood, presence of drying shakes or checks, imperfection of the working, mode (direction, regimen etc.) of the loading etc.

**Figure 9.** Failures caused by bending of clear specimens. Compressed (left) and tended edges (by Giordano, cit.)

**Figure 10.** Typical start of the failure in neat coniferous samples loaded in the medium section
Figure 11 a, b. Beam cracked by bending, general view and detail. The crack extends from the sides to the bottom edge (genio civile)

Figure 12 a, b, c. Bent rafter of a truss of the roof (end of the XVII c.) of the central hall of the Naples archaeological Museum, showing bulging at the compressed regions of the extrados, with small longitudinal cracks.
A recurrent failure of a member of a truss is that of the struts (see before) connecting the rafter to the post, jointed by hinges like joints to both extremities, solicited to point loading when (rather often) too slender; the rupture is rare but the very slow deformation is inexorable and sufficient condition for the failure of the rafter hence of the unit. A secondary but not less severe failure is the deformation of the rafter due to the fact that it loses its middle support; this circumstance generally leads to the crack of the member as a final phase and to further consequences on the joints, units, system.

Quoting from the Encyclopaedia of Wood, a wood member deforms elastically when initially loaded. If the load is maintained, additional time-dependent deformation occurs. This is called creep. Creep occurs at even very low stresses and it will continue over a period of years. For sufficiently high stresses, failure eventually occurs. This failure phenomenon is called duration of creep or creep rupture.

At typical design and use environments, the additional deformation caused by creep may approximately equal the initial, instantaneous elastic deformation. Ordinary climatic variations in temperature and humidity will cause creep to increase.

Unloading a member results in immediate and complete recovery of the original elastic deformation and, after a time, a recovery of approximately one-half of the creep at deformation as well. Fluctuations in temperature and humidity increase the magnitude of the recovered deformation.

Important deformations, even if not specifically dangerous for the member, are anyhow a fundamental cause of failure of the unit and of the system because they generate additional, not planned stresses into the joints, alter the geometry of the units and of the system with the effect of eccentricities and deviations of the stresses.
Worth mentioning is the decay of the wood caused by biologic factors as beetles, fungi, (bacteria) as one of the most frequent causes of mechanical failure.

The fungal attacks, for instance, take place, generally speaking, at the ends of the members when they are inserted into the supporting masonry that transmits the humidity to the wood in a condition of scarce ventilation. The otherwise negligible shearing strains, in a beam at their maximum in the sections close to the support, are sufficient to cause the rupture of the rotten wood, deprived of strength. (Figures 15, 16)

**Figure 15.** Mechanical failure of one beam at its end, in the masonry encasement and outside, caused by decay and weakening of the wood produced by fungi and insects

**Figure 16.** Timber framed building in Paramaribo, Suriname. Complete demolition of the base of a pillar, carried out by termites, in spite of the insulation to humidity from the soil provided by the masonry plinth.

4. Failures of the connections

Amongst the main causes of disconnection of the joints we ought to remember the effects of swelling and shrinkage produced by the fluctuations of temperature and humidity, the ageing of the adhesives, the defects and the biotic damage of the wood, the corrosion of the metallic fastenings, the inadequacies of the design and occasional factors. At the more general level, the effects are reduction of the abutment surfaces and consequent concentration of the stresses on small areas, eccentricity of the stresses, widening of the encasement with occurrence of clearances.

Irregularities of the grain of one ruler ending in one joint turns to be very dangerous for the life of the connection because the affected member, when in place and solicited, is soon twisted by torsion with the consequence of tensions acting not along the main axis but in a different direction, to which the joint is not suitable and wood less strong.

Wrong design of the extremities of the members to connect, that also means insufficient sizing of the shoulders of the joint (see for instance the already quoted case of the failures of the joint tie-rafter caused, in a truss, by imperfect geometry or assembly, excessive stress, lowering of the service stress due to biotic damage etc.), or inaccurate execution of the assembly – for instance, lack of co-planarity of the abutments can cause splitting due to the concentration of the transmitted tensions in a small area - are amongst the most recurrent causes of failure of the connections. (Figure 17)
Figure 17. Monumental complex of Castelpulci, Florence. Break of the shoulder of the chord at the connection with the rafter and sliding (about ten centimetres) of the same piece; the irregular shape of the break is due to the presence of a ring shake.

Rust and more in general corrosion of the iron fastenings, nails or pins, for instance, even if chemical decay of the wood doesn’t occur, have the effect of the embedding of the holes in the wood due to the substantial increase in volume of the metal; in a second phase, with the detachment of the products of the corrosion, the fastening gets thinner in a wider hole, i.e. there is a clearance. Nails are later expelled in a joke of alternated dimensional variations due to changes of humidity and heat. (Figure 18) It is the main reason for finding so many displaced nails on the soil (extrados of the ceilings, for instance) close to the carpentries.

Figure 18. Cathedral (1883) of Paramaribo, Surinam. Original nail from the Cathedral, deeply corroded.

Similar situations of embedding, eccentricity plus deviation, lack of co-planarity etc., with associated torsion, loosening of the joints, alteration of geometry and set up, are to be found in the built-up beams: these are, in fact, more deformable.

Biotic attacks occur frequently in the interior of the joints as a place of lack of ventilation, retention of humidity, dirt etc. specifically depending on design and execution accuracy. Wood is weakened, tenons are shortened and mortises are badly deformed and widened.

(For a description of the most recurrent types of connections, the causes of their decay and the kind of peculiar failure, see Tampone, 1996, cit, p. 172.)
5. Failures of the units

Structural units fail when the connections loose their efficacy (for a description of the most recurrent types of units and of the causes and kind of their decay and failure, see Tampone, 1996, cit.) and of course when one or more members loose their integrity (see above on the cracks of a rafter in a truss or frame).

In the case already quoted of disconnection of the joint of a truss between tie and rafter, a peculiar series of effects at the unit level starts as a consequence. It must be considered that the result of the lower end of the disconnected rafter translating horizontally on the tie and the top extremity sliding vertically on the post is, for the member, a combination of rotation and translation.

The strut is discharged and looses the connection with the rafter (mostly) or with the post (more rarely).

The opposite part of the truss, i.e. the complex post-strut-rafter, rotates rigidly around the opposite joint tie-rafter and starts through the lower end of the post to rest heavily, with its own weight and that of the roof, on the tie. This, a member designed to work only to tension, has been since then subjected to strong bending and therefore deflects severely; deformation is increased by creep if the situation goes on over the time. In some cases the tie breaks.

The described cinematic behaviour is schematically reported in Figure 19.

Geometrical imperfections of the members such as irregularities of the grain or differences in width along the shaft, geometric imperfections of the assembly of the pieces, lack of linearity or not rational position of the loads can have the effect of the unit to twist or, in any case, loose its planarity.

Uneven placement of members in a roof can be cause of ponding and leakage through the covering, absorption of the humidity by wood: a condition of high probability for biotic attack.

Figure 19. Cinematic scheme of the progression of the general failure of a truss caused by disconnection of the left rafter at the joint with the chord (Tampone, 2002). The last phase is the break of the chord with the collapse of the unit.

As a consequence of the irregular assembly of pieces, worth mentioning is the case of the use of long beams squared only half of their length, from the base to the middle, therefore smaller in the other half at the top of the shaft: in a wise assembly of roof beams and floor joists, the members are put alternatively in one sense and in the other. Bad assembly is to put all of them in the same direction, the consequence would be having large parts of the unit much weaker and the construction uneven.

Trusses of the roofs, for instance, are supposed to lay in a vertical plane; when they twist or rotate, in general around the chord and on the supports, they loose almost completely their bearing capacity. The problem rises as a consequence of irregularity of
the shape of the members or because of a defective assembly or in exceptional circumstances such as storms, snowfalls etc., when the top ridge and the purlins of the covering deform intensely or break, thus obliging one of the two supporting trusses or both to rotate inwards. The connection of the joists has the effect of calling also the other trusses to rotation with the general failure known as piling up.

Inefficiency of the floors occurs when the structural components, i.e. the members, fail. Inappropriate sizing of the members and overloading are, in general, the most important causes of failure. Inelastic part of the deformation is also due to creep, a phenomenon due to long term actions.

The crack of the end of the beams is the frequent effect of micotic and entomatic attacks propitiated by the presence of humidity in the masonry and insufficient protection of the wood.

Earthquakes can be an important cause of inefficiency of the floors, of the roofs as well: the walls move pushed by the dynamic thrusts and one of the extremities of the beams goes out of the supports and drops, causing the collapse of at least a part of the unit. Furthermore, in the movement back, the wall is hampered by the heads of the beams giving place to the well known hammering effect.

6. Failures of the systems

(For a description of the most recurrent types of structural system and of the causes and kind of their decay and failure, see Tampone, 1996, cit.)

The ancient structural systems fail when they loose stability and balance especially when the auxiliary members fail or the connection with the units misses its efficiency: the effect on the system is the loss of the continuity, i.e. the loss of the synergy, amongst the components.

In the roofs, to be definitely considered a whole structural system, as said, the shape is essential for the stability: the four-slopes roofs or those with heavy masonry pediments are certainly very steady, in any case more than the two-slopes ones.

At the system level, the sinking of the truss and of the slopes of the bay, i.e. of rafters, ridges, purlins, joists and small rulers, oblige the two adjacent trusses to rotate towards the failing unit thus calling, through the auxiliary members, the other units to rotate and pile up. Piling up can also occur as a consequence of a seismic event. The whole system is upset.
Various factors can change slightly this simple scheme, which keeps anyhow its general validity.

Break of the components, units and members, disconnections are not a necessary condition for the failure of the system thanks to a few favourable factors as elasticity and deformability of the wooden members, ductility of the joints, solidarity etc.

Final failure of the structural systems leads to the collapse of the construction.

A meaningful example of this mode are the Figure 20, Temple of Pagan-gyi in Mianmar, being about to collapse since years, affected by instability and irreversible, severe deformation which is most probably caused by deficiency of stiffness in the posts at the various levels and lack of bracing of the construction. They are an extraordinary witness of structural behaviour; the temptation to take measures to freeze them in the present shape, in order to preserve the unsteady equilibrium as formidable witness of an unusual situation and the proof of the enormous resources of endurance the wood owns, is very strong.

Another example is the Figure 21, Cathedral of Paramaribo, Surinam, Caribbean Region, completely built of wood since 1883; it is affected today with severe general failure due to several factors, amongst which some design faults, overweight of the complex system of roof and vaults, inappropriate interventions at the end of the last century. (Figure 22, Jadlinka)

7. Assessment of the causes

The causes of structural failure are numerous.
A structural failure is generally the result of the action of several factors but are
the mechanical actions that, more than the others, impress their mark on the structure in strict dialectic relationships of causes and effects. Since the mechanical failures are a mechanical matter, the causes of failing should be found between a restricted number of factors, namely suitability of the system to bear the specific loading, which is a matter of configuration, sizing, connections (design, devices, .....,), regimen of the loads, quality of the timber and of the assembly etc. Applied historic research is a fundamental tool in this field.

It must be stressed out that a judicious sizing of the components of a timber structural system is based on the necessity of limiting the deformations more than the strains; furthermore, that the biotic decay of the wood can considerably lower the strength of the material or annul it.

![Church of Jadlinka, Slovak Republic. Failure of the whole timber structural system caused by soil settlements: the central body, heavier than the others, sank pulling the body on the left and, at the opposite side, the bell tower. Both are now inclined towards the centre](image)

**Figure 22.** Church of Jadlinka, Slovak Republic. Failure of the whole timber structural system caused by soil settlements: the central body, heavier than the others, sank pulling the body on the left and, at the opposite side, the bell tower. Both are now inclined towards the centre

### 8. Detection of the failures

**The approach in the practice**

First of all it is fundamental to distinguish the real failures of mechanical nature by the checks caused by loss of humidity and shrinkage of the wood. The checks or shakes caused by drying of the wood are characterized by a few elements namely the V shape of the fissure along the transversal section of the member with apex close to the heart, the placing on the grain though, sometimes, with changes of fibre, the concavity of the affected surfaces of the member. Simple means such as rulers and side lighting can be used to assess if the surfaces of the member, where a fissure is present, have really undergone a concavity (Tampone, 2002, cit., p. 177).

Checks anyhow, in spite of their physiologic nature, reduce the strength of the members. The structural fissures of structural nature are placed, on the contrary, according to the
distribution of the strains depending on the loads; the presence of checks can divert the direction of one or two branches but the general gait remains recognizable. Symptoms are deformations of the construction, loss, even minimal, of the original geometry, mainly verticality, loosening of the connections, breaks, past strengthening interventions; furthermore, signs of presence of water, leakage, changes in colour of some regions of the members. (Figures 23, 24).

**Figure 23.** Cathedral of Paramaribo, Surinam. Boards of the external facing inclined as a symptom of the sinking of the wooden pillar of the right corner, caused by termites and fungi.

**Figure 24.** A sure symptom of low safety factor is the very severe deflection of the ridge and of the slope of the roof in this rural old construction, China (courtesy Mr Michelmore)
Indication that a floor is failing can be excess of its deflection, loss of elasticity, cracks at the extrados in the flooring along the walls etc.

Observation of roofs from outside is very interesting: the wavy outline of the top ridge generally shows that the span between the frames is too large for the size of the member and there is an excess of loading, the presence of an only wave indicates that only one ridge beam gave up and there is the possibility of piling up of the trusses, the deformation of the slope from the rectilinear shape into a curve, which can also be deduced by the accumulation of dust on the slopes and maybe by the growth of vegetation, means excess of deformation of the rafters etc. In the second case cited the ridge beams become a tie.

The consolidations made in the past on a structure are a sure symptom of a critical situation started long ago; the situation of failure sometimes has been cancelled or made invisible but the kind of repair, even if not completely adequate, gives always clues on the previous condition. (Figures 25 a,b, c.)

**Figure 25 a, b, c.** Beam in a tabernacle in Tuscany. a. The presence of iron strip bandage allows the supposition of a crack, asymmetrically placed, of the beam caused by the post in this critical, probably positioned on the major drying shake on the right. The dark colour of the surfaces close to the iron bandage is a symptom of the start of a fungal attack, b. Detail, c. Generalized tear of the wooden surface at the intrados of the beam, out of the bandage, due to tension. The diffused corrosion (rust) of the iron strip shows that the strengthening (or stiffening) measure was taken long ago.
Replacements can be easily spotted by a few symptoms such as colour, grain, surface working, size, position etc. of the new pieces and, of course, of the connection fastenings, in comparison with the ancient ones; the very old wood has a tendency to take up a grey patina.

It is not rare to find several interventions on a structural system or even on an only member, repeated with little variations over the time, to withstand a failure situation. None of them is generally efficacious except, sometimes, the newest. All the added devices give clear indication of the failure.

The accumulation of strengthening devices put in place shows not only the irrationality of the approach but the various sides, components and implications of the failure as well; under this aspect they have to be considered as an important witness. Because the same devices can generally be associated with a certain period of the history of the structural system, they are capable to allow a reading in the sequential, diachronically related sense: failure - strengthening - evolution of the failure - further strengthening. That means possibility of building up the Anamnesis of the whole system.

Direct inspection, checking with elastic waves, radiography, calculation, modelling, construction of the anamnesis etc. are the modern tools of detection, characterization, study of the structural failures.

9. Prevention

The progression of the failures in a wooden healthy structural system is, generally speaking, rather slow; this is also due to the deformability of the wooden members and the ductility of the joints, two factors that prevent the system from immediate breaks. Therefore a number of symptoms make their appearance since the very beginning of a critical situation.

One more fundamental factor, solidarity of the healthy members towards the failing ones, is to be taken into special account. In fact, in a structural system well designed, the connections at any level are efficacious and if happens, for instance, that a rafter of a truss breaks, the auxiliary beams, i.e. the other beams which connect the trusses and bear the covering, in a roof the purlins, will act as ties and keep the broken rafter even if this will sink considerably. It is a very dangerous, temporary phase but the delay of collapse is sufficient to allow the quick adoption of suitable measures.

Many examples of this complex, surprising mechanism are to be found in the practice.

The experienced technician is able, in general, to detect precocious symptoms of failure in occasion of inspections or normal maintenance to the building because the structures, especially the timber ones, are very communicative and express clearly their disease. In order to achieve the task of drawing a complete and detailed frame of the failures present in a structural system, it is here annexed a system of ideograms for the rendering of the failures of the timber structures elaborated by the author (1999) (Figure 26).

The prevention of the middle or extreme phases of the failure is possible because the progression is generally slow.

Several problems can be faced with an appropriate maintenance.
10. Conclusions

In the practice, a wide combination of the failure presented here is to be found. It is demonstrated that the failures of the timber structures are very peculiar, certainly depending on the kind of action, and different from those of the constructions of other materials, besides characterized by a larger number of types. Technicians must be acquainted with them and be able to recognize and interpret them on the spot. They must be able to express an immediate judgement about the level of safety of the construction in the observed condition, take the immediate measures to avoid collapse, delaying to a further accurate survey the full evaluation of the general situation.

The full understanding of the failures of an existing structural system can greatly help to interpret its behaviour, inconsistencies, shortening of the level of serviceability. Similarly, the full understanding of an old structural system, reducing the number of unknown factors, allows a direct and appropriate design of the strengthening measures and devices, the cutting down of the extent and quantity of the intervention with evident advantage for the costs but more for the conservation of the authenticity of the ancient surviving specimens. The risk, otherwise, is to make useless or, worst, harmful interventions. To prevent this regrettable situation, the strengthening measures must be designed only by technicians who are familiar with the peculiar way of failing of the timber structures and capable to enter into their conception.

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