# The Failure of the Timber Structures Caused by Incorrect Design-Execution of the Joints. Two Cases Study

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## 1. Introduction

Timber structures can be compared to real machines whose efficiency (supposed for decades or centuries) is strictly linked to the right and rational design of the structural system, of the structural unit, of the structural elements and of the joints.

Examples of perfect design of the connection joints are very common in Renaissance carpentries. However, we can find a great deal of examples wrongly realized in common constructions.

Examples of wrong realizations are more frequent in the XIX century.

From the analysis of ancient wooden carpentry handbooks we can note how the old treatise writers illustrated timber structures with an incredible high definition. In fact the design of the structural units and the connection joints was extremely accurate and referred to the geometrical schemes: the metallic devices for regulation and tighten were very clearly represented.

It is very common to find irrational timber structures coarsely realized. In many cases we can justify a wrong execution because these structures were realised to be hidden from other structures like ceilings, vaults etc...

In other cases the reasons for these wrong realizations can be found either in the difficulty to track down well dimensioned elements or in the low ability of workers, or designers if they ever existed.

The design of the structural unities presents a large number of solutions. This number derives from several aspects such as the shape of the rods, the dimensional relationships, the number of the structural elements and from the slope of the rafters which derives from climatic conditions. Besides, the presence or not of ancones changes with the span.

It is not rare to find timber structures whose degradations are caused by an inefficient work, consequence of a wrong design or execution.

Very common mistakes are made in the realization of connection joints between structural elements. Often, these mistakes can produce a crisis of the whole structural unit.

The incorrect execution of the joints can produce a not homogeneous distribution of the stresses with consequent high deformations, breaks, and kinematic movements. With this kind of stress, the contact surfaces between the structural elements cannot be uniformly stressed.

A different set-up of the trusses can produce the following problems: localized hollow of the pitches with stagnation of rainwater, water infiltration in the garret, increasing of the humidity with consequent creation of favourable biotic attack conditions.

A right diagnosis of the failures can be achieved with careful and specific remarks and with a survey carried out to determine the exact joints geometry and their possible lacks.

In fact, the inspections are not easy because of the lack of illumination and of the difficulty to reach the joints safely for the observations.

**Figure 1.** *Palazzo Altieri (Roma).* Passing trough crack (splitting) of the rafter of a truss, placed on a previous shake, caused by wrong execution of the joint. In the picture it is evident that only the upper part of the end has close abutments, the inferior surfaces do not touch

**Figure 2.** Palazzo Altieri (Roma). Crack of the clog of the connection section of the rafter of a truss caused by insufficient sizing, wrong design. The presence of humidity stains allows the suspicion of decay of the wood caused by biotic attacks. Note the multiple splitting fissures along the fibres in the sections close to the indentation and the bending of the lower fibres bundles

## 2. Cases study

In some cases the origin of the failure depends on the wrong geometry of the structure, for instance we can cite a few trusses of the timber carpentry of the *Palazzo Vicariale* at Certaldo.
This architectural complex is composed of constructions dating from different ages and modified until the late 1970s.

During the restoration, made by Luigi Del Moro (from 1890 to 1907), the new structural units for the support of the roof of the *Sala del Vicario* were achieved. These structural units are not very well constructed and in addition they present a grain deviation.
This situation should be justified because the cited structural units were constructed to be hidden by a ceiling. They are very classic trusses with king post and rafters, without struts and with a span of 8.4 meters.
The joint between rafter and chord is realized by a cogged joint.
In some cases we can find a timber ancon with an iron bandage, probably placed subsequently in order to prevent the ancon rotation.
The connection joint is out of the wall surface.
In this case the vertical resultant of the interior stresses of the two rods does not completely fall in the wall surface.
Consequently the exterior part of the chord is undergoes a bending stress produced by the vertical reaction of the bearing and by the vertical component of the interior stresses.
The results of this incoherence is immediately perceived in a big deformation of the chord.
The timber is a material which, if subjected to high loads for long times, deforms itself more easily than other materials.
At the same time we can note a break in correspondence with the joint. This break causes the sliding of the rafter on the chord. This sliding is also caused by the bad quality of the wood which presents an irregularity and deviation of the grain.

The structural failure increases and starts a reiterative process, because the running of the rafter makes the king post touch the chord (the chord is stressed from bending moment).

**Figure 3.**Palazzo Vicariale of Certaldo. Severe deformation of the rafter of the truss of the roof of the Sala Vicariale in the sections under the clog, splitting of the rafter at the connection with the chord indentation, severe deformation and crack of the chord close to the collar tie, splitting of the ancon.

**Figure 4.** Palazzo Vicariale of Certaldo. All the failure scenario is caused by erroneous placing of the node of the truss on the wall with the indentation out of the support: the reaction of the load transmitted by the rafter on the chord and the reaction of the wall support produce a bending moment which, over the time, generated the deformation and the crack.
The timber ancon, the brick ancon and the collar tie are insufficient measures taken in a close past; the collar tie does not connect, as it should do, the three convening rods

**Figure 5.** Palazzo Vicariale of Certaldo. Typical fissures and generalized cracks of the wall support of a truss, caused by excessive pressure on the edge of the masonry support following the deformation and rotation of the chord

This example shows that design and geometry with the absence of the necessary tighten systems (metallic ties) have an important function for the efficiency of the joints.
We can suppose that these wrong configurations were not made by mistake, but were justified by reasons like the lack of availability of long enough rafters. However in these cases, carpenters usually put stone ancones to enlarge the bearing surface so as to make the resultant fall in correspondence with the wall surface.
For this reason a wide use of ancones made up of timber struts inserted in the masonry, was very common.

A very significant example is the system designed by Giorgio Vasari for some trusses of the *Salone dei Cinquecento.* Here the increasing of the bearing surface is assured by the presence of two stone ancones where enormous timber wedges rest. These wedges are the regulation mechanism which assures the tighten between the stone ancones and the intrados of the truss bearing surface.
A timber strut placed exactly under the timber ancon of the truss provides an additional support and alleviates the timber wedges from the high concentration of the load.
Common degradation caused by wrong design or execution can be found in the simple overlapped connections between rafter and chord.
The hand workers rely on the action that the masonry can offer to prevent the rafter from sliding on the chord.
In the case of a very thin masonry, the diaphragm that divides the woods from the exterior, could be extremely little and unable to support the stress.

Another hindrance to the sliding is the masonry weight on the rafter. Frequently, metallic ties are not present, while they would be useful since they block the sliding of the rafter on the chord.

To ensure the right work of metallic ties, ancones are engraved so as to be connected to the indentation of the rafters.
Sometimes, the cause of the failure is not immediately detectable. The connection joints between the structural elements can be partially or completely hidden by other structural elements.

Only after an accurate examination and a survey to detect the joint geometry we can link this to the origin of the failure.
For instance, we can quote the case of the failure of one of the trusses built by Giorgio Vasari in 1563 to support the roof and the ceiling of the garret of the *Salone dei Cinquecento*.
Of the whole structural system, composed by twelve trusses of enormous dimensions, excellent for the geometry, the quality and the manufacture of the timber, (25 meters of span) only one truss showed such a high displacement to require, the realization of a strengthening work in the first part of eighteen century. This ancient very rational strengthening work, is representative of this kind of failure.

The chord is connected with the rafters by two big wrought iron collars, equipped with regulation devices. These collars have the task to block the displacement at the bottom of the chord.
A quick examination may produce a misunderstanding of the causes which made the bending of the chord, composed of two connected parts because of the big dimension of the truss.
Only accurate observations of the space between the chord and the ancones made it possible to understand the geometry of the connection joint.

The connection joint of all the chords is made, according to the type so called “Jupiter’s arrow”, with inclined cuts of he ends of the two pieces, clogs and related indentations, locking bars. Two timber ancones, one placed at the upper surface and a smaller one at the lowest surface, are connected to the member by iron collar ties equipped with adjustment devices; but the presence of nails along the tie to connect iron and timber makes the adjustment impossible (therefore the nailing is, most probably, a following intervention). Nails and keys improve anyhow the connection; an usual prevention measure against the excessive deflection of the timber tie is the vertical iron collar tie nailed to the post, here present too, that passes around the timber tie. The ancones play the role of stiffening the joint; this is, therefore, completely hidden.

The cited truss is similar to the others except for the different length of the two component pieces, one is 15 m, the other 12, with a difference in weight of about 300 kg. The truss is not symmetric because the intermediate connection is not in the centre.

The deformation is asymmetrical as well.

**Figures 6,7,8.** One of the Vasari's truss. Insertion of wooden strut, stone ancones and large wooden adjustment wedges, meant to obviate the inadequacy of the masonry support

**Figures 9,10.** Palazzo Vicariale of Certaldo. Connection by simple over position of the rafter on the chord in the main joint of one of the trusses

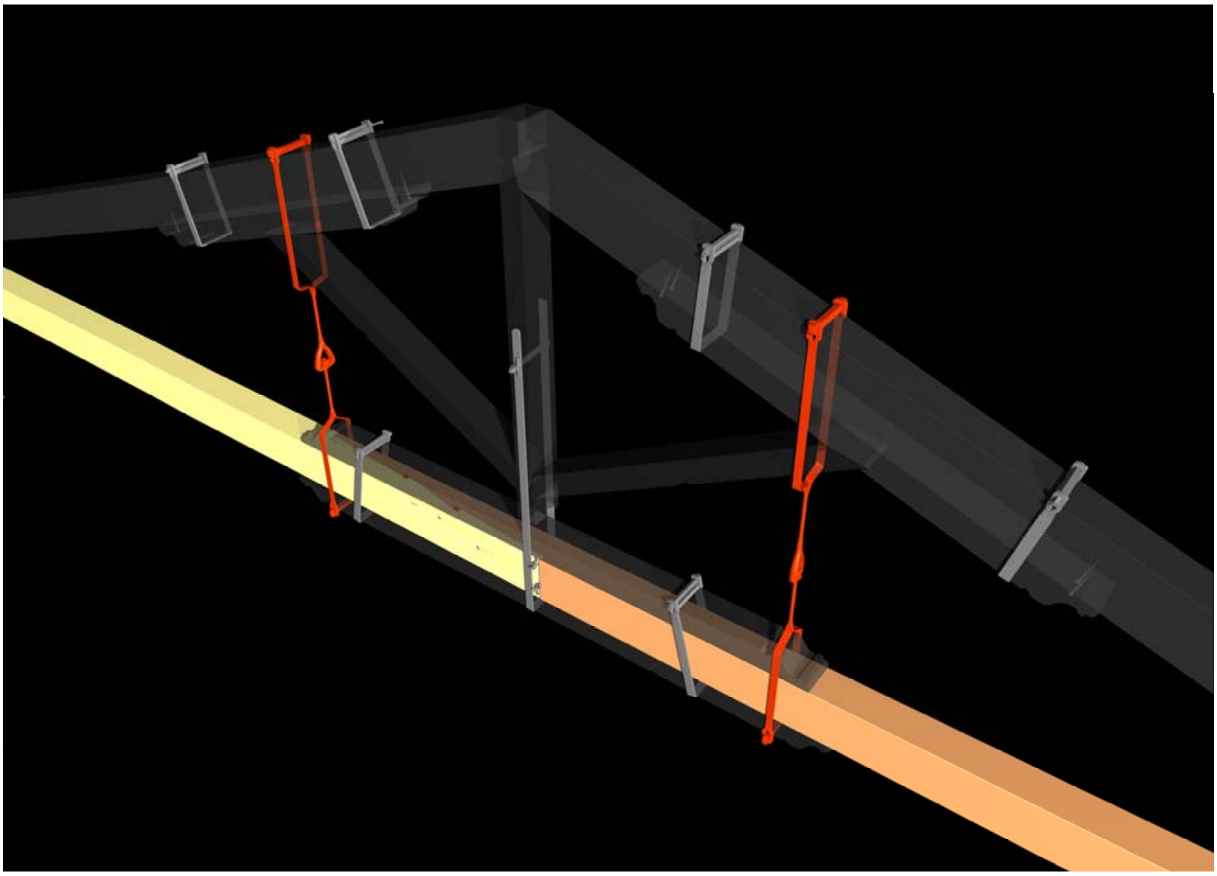

**Figure 11.** Vasari's truss, 3d model. The Jupiter's arrow connection is not put in the middle but sideways. Only by means of the two iron suspenders (red in the figure), placed in the first half of the XIX c., prevent from rotation the two stumps of the chord

**Figures 12,13.** Wrong position f the metallic keys that should have connected rigidly the two components of the chord. The photo on the right shows the break of the abutments

**Figures 14,15.** The Vasari's truss. The mutual rotation of the chord and of the ancon

## 3. Conclusions

Unsuitable design and lack of accuracy in the execution of a timber carpentry could seem negligible circumstances to the builders but, over the time, they prove to be a real problem that can affect the whole system and reduce considerably the safety factor.

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