

Analysis and repair of historical roof structures: Two examples, two different concepts

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Two historical roof structures are presented. The history and sequence of alterations, damages and deformations during life time is described. The history is the key for understanding the damages and for developing the appropriate repair concepts. The two structures are similar but the alterations they suffered are different. A suspension truss is the main feature of both structures. Both structures show big deformations, but caused by different reasons. Two different concepts of repair measures are derived. The advantages and disadvantages of the measures are discussed.

INTRODUCTION

Historical roof structures are an important part of the cultural heritage. The objective of every repair concept should be to secure the statical stability, to minimise the alterations of the historical substance and to preserve the architectural form. The basic requirement for the development of a repair concept is the precise understanding of the damages and deformations.

Damages can have a lot of different reasons. A precise and detailed assessment of the damages is essential. In a lot of cases the history and the sequence of alterations and deformations during the life time has to be reconstructed in order to get an explanation for the present situation. Statical calculations considering different stages of alterations can help to understand the sequence of reactions.

ROOF STRUCTURE OF A TOWN HOUSE IN MUNICH

A model of Munich dated 1572 shows the building of Burgstrasse n° 8. It is the building with the huge roof (Fig. 1). The roof structure still existing today was erected in 1615 and has the same shape as the roof in

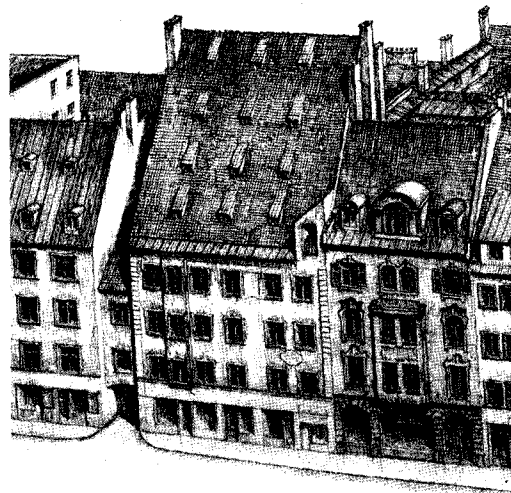


Figure 1
Townhouse Burgstrasse 8 in Munich. Drawing based on a town model of Sandtner dated 1572 (Häuserbuch der Stadt München)

the model. It is completely original. The structure is shown in Figure 2 and 3. There are four storeys inside the roof. The struts at the first floor are not part of the original structure. They were added in the last century. The free span of the was 21,10 meters from the eastern to the western wall of the building. The distance between the north and the south gable wall is 14,30 meters. The height of the roof structure from the eaves to the ridge is 13,90 meters.

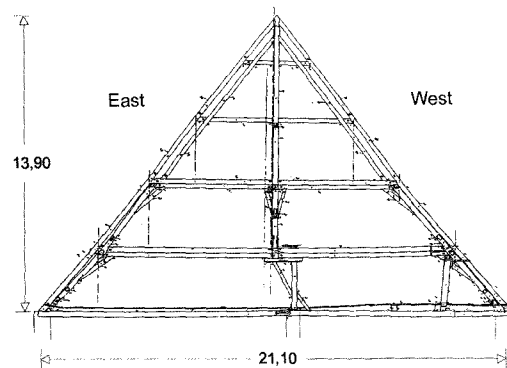


Figure 2
Cross section (Drawing of Franz Hölzl, Munich)

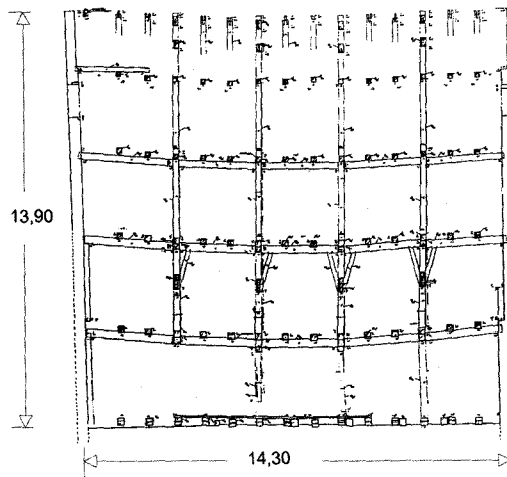


Figure 3
Longitudinal section (Drawing of Franz Hölzl, Munich)

The structure consists of 14 rafters at each side connected by horizontal beams at five levels. In addition four principal trusses stiffen the structure. Above the first storey a continuous beam with a cross section of 27 by 30 cm is spanning in longitudinal direction between the gable walls. This beam is hanging at king posts which are connected to a suspension truss in the third and fourth storey (Fig. 4). In the year 1726 an additional truss was built in at the first storey parallel to the west side (Fig. 5).

The damage assesement shows the following:

1. Along the eaves on the west all joints between the ends of the rafters and the anchor beams are rotten.

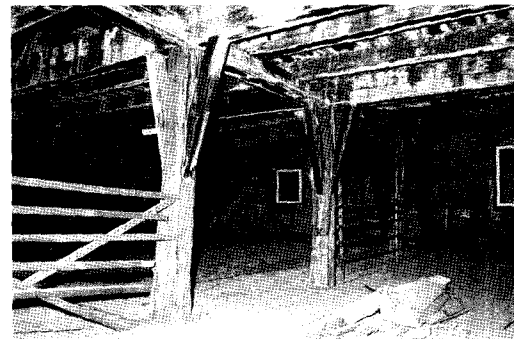


Figure 4
Second storey inside the roof structure, the king posts in the middle axis

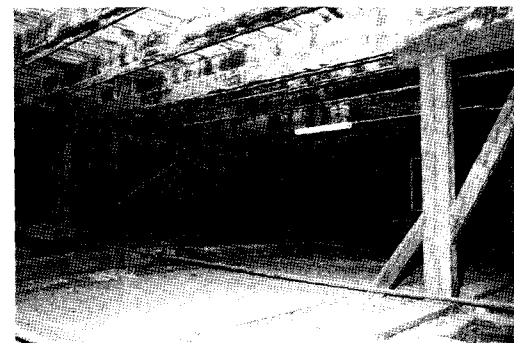


Figure 5
First storey inside the roof structure, the truss visible in the background dates from 1726

2. A lot of joints are drawn apart, especially in the upper part of the structure. Wooden nails are broken.
3. There are big deformations of the upper floors. The sag between the gable walls is 42 cm (Figs. 3 and 4).

Analysing the damages and the deformations joint by joint it was possible to reconstruct the history of the roof since the erection.

Soon after the erection damages along the eaves at the west side occurred due to a leaking roofing (Fig. 6a and Fig. 8). The joints between the rafters and the anchor beams were destroyed and failed. The rafters slid outwards and down to the masonry. The entire roof settled and got into an inclined position.

About a hundred years after the erection of the roof the truss was added in order to stop the movements. This truss took the big vertical loads of the roof and prevented the roof from further vertical movements. However the truss caused additional damages. The truss is a vertical support not a horizontal one. The horizontal thrust of the roof had no support. A new mechanism was created (Fig. 6b). The entire roof moved to the west. The truss got inclined. At the east side the movement to the west also caused a vertical movement. The lower support is a centre of rotation for the struts of the principal trusses. This movement was hindered only by the rafters. The rafters are continuous beams going from the eaves to the ridge. As a result the connection between the rafters and the principal trusses were drawn apart (Fig. 9). The wooden nails failed.

At the end the settlement of the upper floors was 42 cm. The struts were built in order to create a support in the middle of the span (Fig. 6c). The self load of the roof is now supported by these struts. The forces in the suspension structure changed from tension to compression. Some joints which were designed to take tension forces only could not take compression forces and fell apart.

The deformations described occurred in the middle between the gable walls. At the gable walls the movements are restricted because of the connection of the structure to the masonry. A complicated three dimensional deformation figure was created (Fig. 7): At the west side all rafters slid downwards. Braces connecting the gable wall and the structure failed. At the east side there was no settlement at the eaves. The

horizontal beam at the second level, running from gable wall to gable wall, was bent but did not fail. The deflection line shows a horizontal and a vertical component. In a similar way the heavy beam in the middle was bent. It is also fixed at the gable walls. Therefore the three dimensional deformation figure

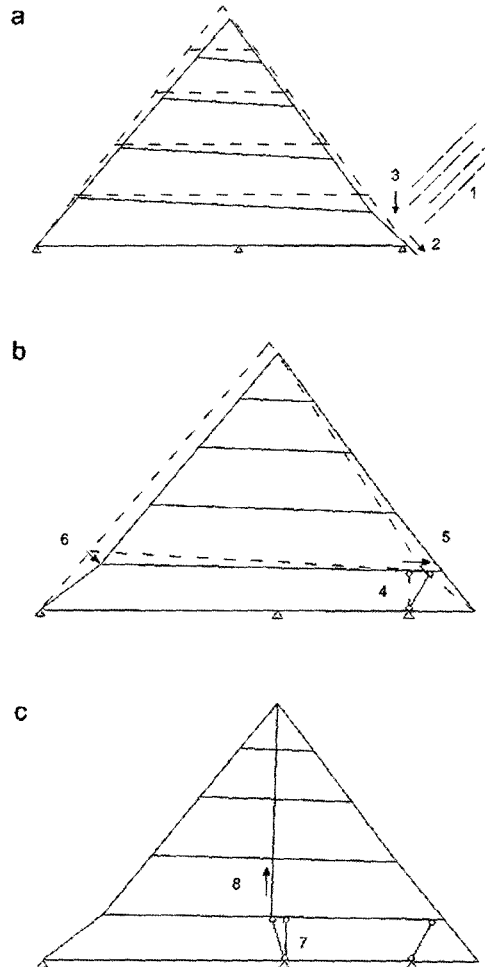


Figure 6

Sequence of damages and repair measures 1) leaking roofing 2) destroyed connections between rafters and anchor beams 3) vertical deformation 4) new truss in order to stop the deformation 5) horizontal deformation 6) rotation of the inclined strut 7) new columns in order to stop the vertical deformation 8) compression instead of tension

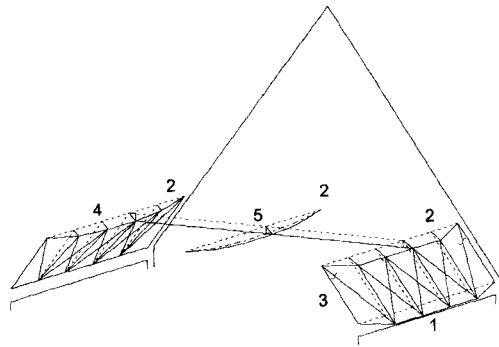


Figure 7
Three dimensional deformation figure

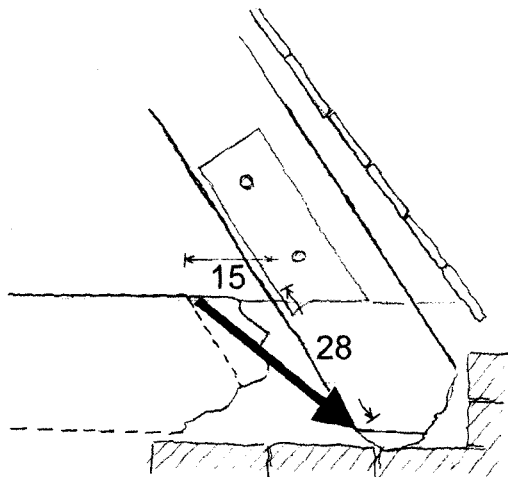


Figure 8
Damages at the west side

shows a big settlement only in the middle. Deflection lines due to bending are visible only in the longitudinal section (Fig. 3) but not in the transverse section (Fig. 2). The structure was prevented from collapse mainly by the horizontal beam at the middle axis.

On the basis of these results the repair concept, which was proposed, intends to push the structure back to the original position and to take out the big deformations. Experience shows that it is practicable. However it is expensive. It is not yet realized. It will

make it possible to restore the original statical performance without introducing a lot of additional elements. In the present situation it would be nearly impossible to repair all the joints which are drawn apart. Big steel elements would have to bridge the gaps. Removing the structure into the original position it will be possible to bring the joints together again. Then it will be possible to repair the joints in a reasonable way. The forces will be taken out of the truss along the west side. However it should remain in the roof. The struts in the middle will be taken out. A statical analysis of the original structure shows that it will be stable. Only a few additional elements are necessary in order to secure a sufficient safety factor under wind and snow loads.

ROOF STRUCTURE OF THE «ALTE HOF» IN MUNICH

The historical roof structure of the «Alte Hof» in Munich is the second example (Fig. 10). The main feature of the structure is a suspension truss, too. The «Alte Hof» is a castle founded in the 12th century. It has been the residence of the German Emperor Ludwig the Bavarian from 1328–47 (Burmeister 1999). The oldest part of the historical roof dates from 1525 and is one of the oldest original roof structures in Munich. The part which is presented in this paper dates from 1562 (Figs. 11 and 12).

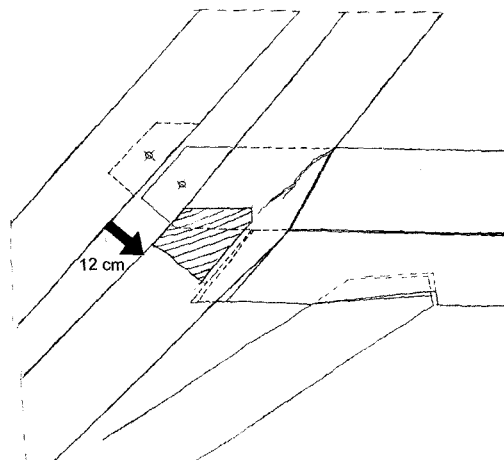


Figure 9
Joints drawn apart at the east side



Figure 10
«Alter Hof» Munich

In the original situation the roof structure had a free span of 13,35 meters. It had to take the load of the ceiling above a huge hall. The ceiling is rather heavy due to a filling between the beams. The beams are supported in the middle axis by one big upstand beam. Its length is 18m and its cross section is 40 by 30 cm. This beam is hanging at suspenders consisting of wrought iron. They are anchored at the suspension truss situated in the upper storeys.

There are three storeys inside the roof structure. In the first storey the struts of the principal trusses are

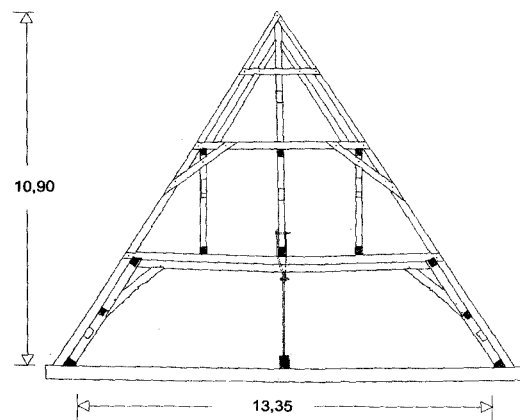


Figure 11
Cross section of the roof structure

inclined parallel to the rafters. The suspenders which are made of wrought iron instead of timber and the ornaments at the braces are indicating that the first storey was considered as a space of high value. The construction of the ceiling is also rather heavy and was painted.

In the second storey the struts of the principal truss are in a vertical position. Braces are connecting the horizontal beams and the rafters. In the middle axis there are the king posts and between them a very stiff bracing in longitudinal direction. A lot of elements are decorated by wood carving. Even the joints themselves are carved work. In the third storey suspension trusses take the vertical loads of the middle axis.

At a later time a wall was erected in the storey underneath the roof exactly in the middle of the structure. The new wall acts as a support for the ceiling and the first storey of the roof. It takes out the forces of the suspenders.

The damage assessment of the present situation shows the following:

1. local damages due to a leaking roofing, mainly at the west side
2. big deflections at all the floors
3. broken joints due to overloading, especially at the connection of the braces and the rafters in the second floor (Figs. 13, 14).
4. local damages caused by fire. These damages are dated from the time of second world war. The repair was done very roughly.



Figure 12
First storey inside the roof structure



Figure 13
Second storey inside the roof structure, connection between rafter, brace and vertical strut

The analysis of the statical behaviour and the sequence of alterations and damages lead to the following conclusions (Fig. 15):

During the first period of time the structure had to span 13.35 meters and had to take the entire load of all floors. The suspenders and the suspension truss itself were strong enough. But there were problems in transferring the forces to the outer supports because of the distribution of stiffness inside the overall structure. The load path with the highest stiffness is the path from the suspension truss directly to the braces and to the rafters. The principle truss is not as stiff as the rafters due to the deflections of the horizontal beams which support the vertical struts. However the joints between the braces and the rafters were not strong enough. They are halved joints with

carving. Deformations occurred and the principle truss had to take over the loads. Bending moments caused big deflections. A statical calculation, considering the damaged joints at the rafters, confirms that.

Probably the deflections were the reason for the wall which was built underneath. The wall took over the loads of the floor. The forces at the suspenders and the suspension truss were reduced. However further deformations occurred and the suspenders buckled.

At the beginning of our work it was intended to strengthen the suspension structure in order to establish the original flow of forces. The consequence of that would have been to replace the destroyed joints or to introduce an additional steel frame. To replace the joints was unacceptable because of the carving works. Even a copy of the original joint would not be sufficient. The acting forces at this point require a total different type of joint.

The result of a lot of discussions was extremely simple. Upon the upstand beam in the first storey along the middle axis a few small steel columns were positioned. They take the loads of the upper floors and transfer them directly to the middle wall underneath. The king post is now under compression instead of tension. The compression is very small and the design of the joints make it possible in this case. The stiffness of the entire roof structure became much higher even against horizontal loads. No further



Figure 14
Overloaded joint between rafter and brace in the second storey

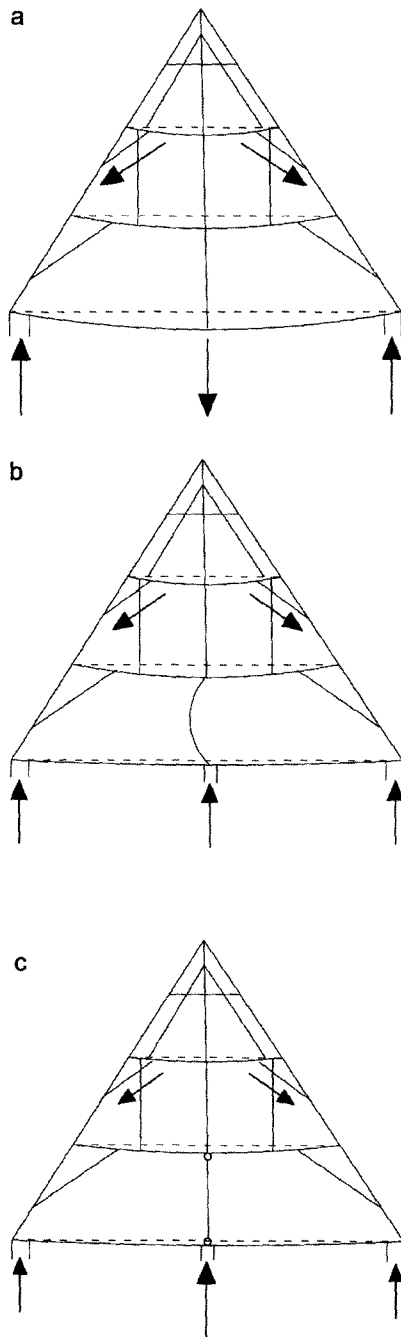


Figure 15
Sequence of statical systems

measures were necessary. The overloaded joints could stay in place without repair. They are a part of history.

The disadvantages of this solution are:

- The original flow of forces is altered. From an engineering point of view it could be desirable to re-establish the free span. That is a historical value as well. On the other hand it has to be stated, that the structure never really worked like that. Originally it was intended but the joints were too weak.
- The columns disturb the big space at the first storey. From an architectural point of view this is not acceptable, even if the space is not used anymore. In this case, the space was already divided into two parts in former times. A few timber elements are still in the middle of the room and they remain there. The columns are not the only elements which disturb the space.

CONCLUSION

The examples demonstrate the importance of a precise assessment of the damages. The history of the alterations and of the damages can be the key for the understanding of the structure. The statical analysis has to consider different situations. The objective of repairing old structures is not necessarily to re-establish the original situation. The repair measures are a further step in the history of the structure.

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