Historical Timber Structures – Mechanical Patterns and Structural Form

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For a number of years the Department of Architecture at Chalmers University of Technology has been involved in studying historical timber structures. One of the goals has been to develop a qualitative language for describing how these timber structures function as load carrying structures, with the aim of facilitating professional dialog between engineers, architects, historians, antiquarians and craftsmen. A language of this sort helps to enrich knowledge of the historical development of timber structures through considering the central dimension, how their mechanical behaviour and effectiveness is affected by changes in form according to historical ideal and accessible technology. A possibility to better integrate the mechanical action as a value for preservation can then also be gained.

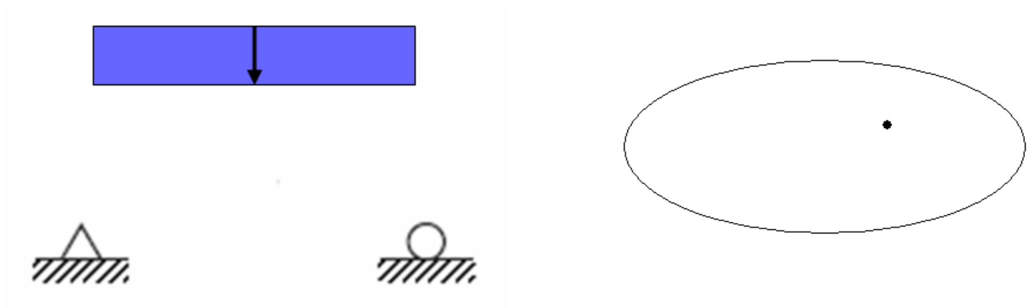
Both historians and antiquarians have posed certain questions to us regarding the functioning of historical timber structures, questions that Sandin [1] has formulated as follows: ”How do the roof trusses of old churches act as load-carrying structures?”, ”How does their design affect their mechanical behaviour?”, and ”What forms are most rational?” She has created an explanatory model that facilitates qualitative reasoning about how such roof trusses function and has applied it to a selection of roof trusses from 18th and 19th century neoclassical churches in Sweden characterized by a particularly large roof span, the largest of these being 18.8 m across. Thelin [2] pursued Sandin’s questions further, studying changes in the design of roof trusses that the transition from Romanesque to Gothic style brought about, the removal of tie beams having markedly affected how roof trusses behave mechanically. Parallel with Sandin’s and Thelin’s work and inspired by them, Olsson [3] investigated the structural mechanical theory involved, searching for alternative conceptions and tools for explanation and interpretation of what could be observed. He proposed a manner of describing structures applicable both to the analysis of existing structures and to the process of designing new buildings. The descriptive model proposed is coupled with a form of visualization making it easier for persons from the various professions involved to obtain both a visual and a verbal understanding of the phenomena and the patterns of forces that constitute the basis for the structural behaviour and structural form that evolve during the designing process. The model contains two central concepts, those of ’structure’ and of ’quality’, use of which allows mechanical effects introduced by changes in material or form to be studied qualitatively.

The engineer’s understanding of structure is closely linked in many respects with the language used in the everyday work of sizing structures according to norms. Three basic aspects of this language are important: 1. that a structure be adequately specified in terms of form, material and external support, 2. that the loads assumed be as realistic as possible, and 3. that the strength of the materials involved be known. A computational model of a given structure is created and is tested for different sets of loads. For each load case, measures are obtained of the risk to various parts of the structure of failure. The key terms of the language employed are those of *computational model*, *load case* and *strength*. With use of such a language, oriented to local stress (and deformation), the understanding of a given structure easily becomes linked with the sizing of the elements it contains. Although such a procedure can function well for the purpose for which it was designed, above all that of preventing a structure's collapse, this way of describing structures and the language it involves have clear limitations in terms of providing an adequate basis for investigating and describing a structure's overall design in terms of its effectiveness in a more general sense.

An alternative approach to understanding structures based on the stress pattern created in the field between a given load and a particular set of supports can be formulated. Such a stress pattern can be investigated qualitatively by use of three separate components: *the structural task, the material stiffness* and *the shape of the body*. These can be explored both during the process of designing a structure and in a historical analysis of the development of a particular structural form. The process employs two central concepts: 'structure' and 'quality'. 'Structure' refers to the inner pattern of forces (or stresses). These can be basically of two types: the pattern of forces created by axially directed load paths (such as in trusses), and the pattern of forces representing the principal stresses found within a continous body. The term 'quality', in turn, refers to the visual images and the verbal accounts and meanings enabling the recipient to do the following:

- to perceive a direction of change that occurs (helping one understand why something becomes better or worse)
- to see and to understand where borders lie (including the presence of instability)
- to discover possibilities for exchange (exchange material for form)
- to comprehend how different goals and values can support or counteract each other (such as structural strength, tough or ductile collapse, structures showing "give" when movements of the ground beneath occur, etc.).

The concept of 'quality' takes as its point of departure the pattern given by a 'structure'. It is a measure on how close to this pattern the physical structure comes. It can be used as a tool for exploring how changes in material and shape affect a structure's effectiveness, and also to explore the behaviour of a structure if of a change in the structural task occurs. Such a qualitative investigation of a structure requires an understanding of the structural and continuum mechanical concept of stiffness.



Load and support **Region involved and material characteristics**

Figure 1. External and internal conditions

A further alternative approach to understanding and reading a structure is to distinguish between the *external* and the *internal conditions* to which a potential or actual structure is exposed, a limited set of external conditions being seen as representing the general load types and support conditions constituting the most extreme cases that can be involved. Sandin [1] defines the 'task' a roof truss is to fulfil through its possessing an appropriate 'design' as a specific combination of external loads and support conditions. Each task is designated in terms of the force pattern characterizing it, as shown in figures 2 and 3. The diagrams in figure 3 motivate the names the 'tasks' shown there have been given.

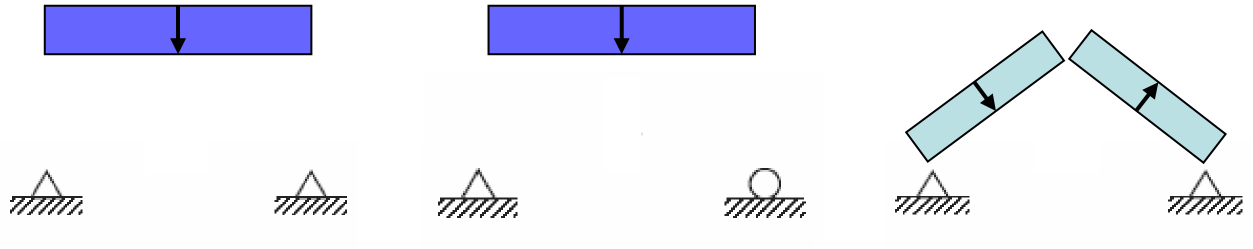


Figure 2. Support 'tasks'

Figure 3: 'Structure' identified in terms of the principal stresses involved, providing the basis for Sandin's naming of the three different types of 'task'

Through use of the two 'tasks' at the left in figure 2, Sandin explores the structural design of roof trusses subjected to such loads due to gravitation, and for a scale of horizontal support ranging from completely rigid to completely lacking in external horizontal support. By comparing the 'task' at the far left with that at the far right in figure 2, she is able to show which parts of a roof truss play an effective role in supporting the gravitational load and the wind load, respectively. Figures 4, 5 and 6 show how these patterns become visible and readily identifiable for roof trusses of differing inner form. The concept of 'quality' plays an important role in interpreting the figures and in identifying what roof truss forms would be most rational. The pattern of internal forces is strongly affected by how successful the truss form in question is in creating stiff internal load paths.

In figure 4 the *normal force diagrams* in the right-hand column can be understood as being combinations of straight thrust lines (a form of arch), whereas the *moment diagrams* in the central column shows how transverse loads are transmitted through local bending to the joints of the roof truss. The concept of rationality here is linked partly with how an effective design of the roof truss being is to create thrust lines, and partly with how rationally placed collar and scissor beams can provide support for the rafter that results in an only limited curvature (bending). Table 1 provides a comparison of stresses due to bending and due to normal force at the joint where the collar beam meets the rafter (marked by a black point in the figure).

Table 1.

Roof truss number	Stresses due to bending	Stresses due to maximum normal force
1	5 Mpa	0.1 Mpa
2	2 Mpa	0.3 Mpa
3	2 Mpa	0.3 Mpa
4	1 Mpa	0.2 Mpa

In figure 5 the force pattern shown is largely a response to how the design of the different trusses is able to provide load paths for the tension in the bottom portion of the trusses. For the two upper roof trusses, in which scissor beams are lacking, the tension force is led from the collar beam to the support through bending of the rafters (tension at the lower edge, cf. the middle part of figure 3), this resulting in a large bending moment. The two lower roof trusses exemplify the importance of a rigid ‘anchoring’ of the internal load paths. The bottom-most roof truss contains elements that provide a stiff anchoring of the tension line extending along the bottom part of the two scissor beams. Here a vertical supporting line (the King’s post) is attached at the apex of the tension line and is anchored at top of the truss, where the joint allows there to be equilibrium of normal forces. Such is not the case in the roof truss directly above it. The anchoring at the apex of the tension line is transmitted to the rafters here primarily by the scissor beams, the bending of the rafters providing support. Whereas support by bending generally results in weaker support, the roof truss as a whole becomes weaker here, resulting in larger deflections. Also, the bending moment of the rafters increases, due to their support of the tension line of the truss.

Figure 6 shows how roof trusses act in response to wind load in general. The collar beam alone is unable to counteract the bending of the rafters, but in combination with the scissor beams it is able to divert a part of the bending from the rafters to the scissor beams (cf. the right-hand part of figure 3).

The reflections evident in figures 4, 5 and 6 show how a qualitative dialog concerning the efficiency of a particular roof truss design can be performed. The effects of the form and placement of the different components of the roof truss in relation to the different ‘tasks’ can be assessed. A qualitative analysis of the behaviour of a roof truss exposed to damage can be carried out in a similar way.

Sandin presents four basic points a study of historical timber structures should attend to. Two of them concern what should be investigated in assessing the inner form of a roof truss:

- Whether the design creates axial load paths (normal forces) sufficient to provide the stiffness that the ’tasks’ require
- How the design affects the size of the outer acting and the inner reacting moment. This governs the size of the horizontal thrust.

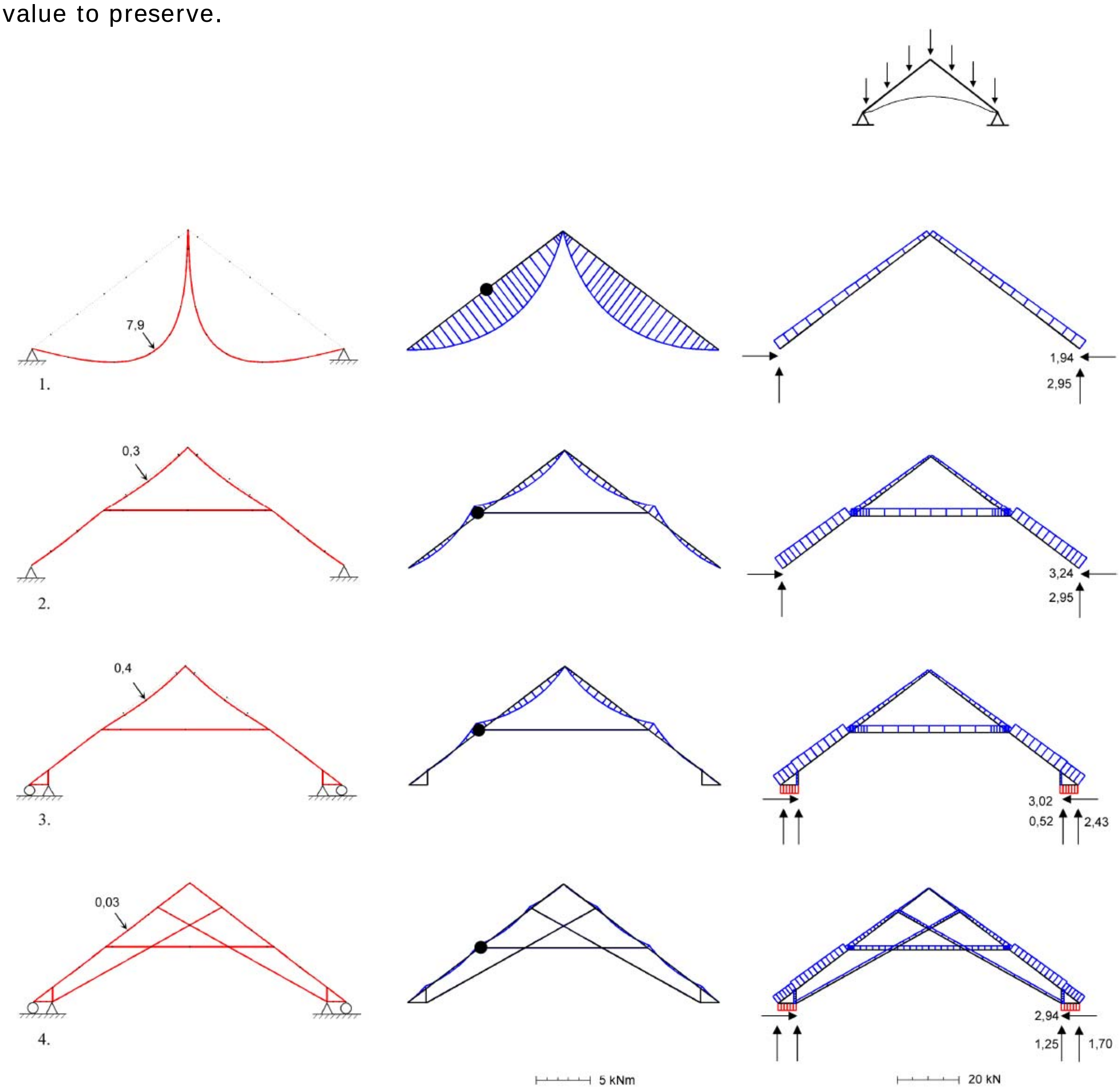
The other two points concern the internal loading of the rafters that are bent:

- How the rafter transmit transverse load to stiff (axial) load paths (through bending).
- The relative stiffness of the supporting stiff load paths created by the inner form of the roof truss. This determines the extent to which the rafter is supported along its length**,** and thus the degree to which it is able to carry its load.

These last two points permit an evaluation of how effectively the rafters meet an external transversal load and transmit it to load carrying elements able to more effectively carry the load (axially).

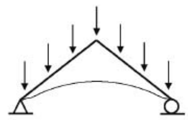
Whereas Sandin investigated the effectiveness of a limited number of roof trusses of differing internal design, Thelin decided to use this approach in a more general way. He limited himself to Sandin’s second ’task’, that of ”support by compression and tension”, although he computed instead the quality of several such roof truss designs. This ‘task’ is oresent when a tie beam is lacking or its stiffness has been reduced. He introduced a scheme in which he organized the inner structures in terms of the space they occupied, figure 7. He then compared them quantitatively in terms of their stiffness,

figure 8. Striking about the results was the fact that the presence of axial forces in the structure played a major role in determining the effectiveness of the system.
Both when historical timber structures were originally built and when later changes in them were made, thorough discussions were surely conducted between the client, the building contractor and the craftsmen involved, concerning questions of how the structures carried loads and how the design of the structure could best satisfy the spatial functions aimed at and ensure both effective use of the building material and that the building would not collapse. Our desire has been to use structural mechanical principles as a basis for similar discussions between present-day actors with an interest in structures of this type. We hope to be able to contribute, through use of more adequate verbal and visual means than employed earlier, to the knowledge of the mechanical behaviour of historical timber structures. Our aim is that those making antiquarian judgments then better will understand how to integrate the structural behaviour as a value to preserve.



A. Deformationsfigur B. Böjmoment C. Normalkrafter och stödkrafter

Figure 4. Roof trusses analysed for the 'task' type 'support as an arch' from Sandin [1]. To the left deflections, in the middle bending moments, and to the right normal and reaction forces



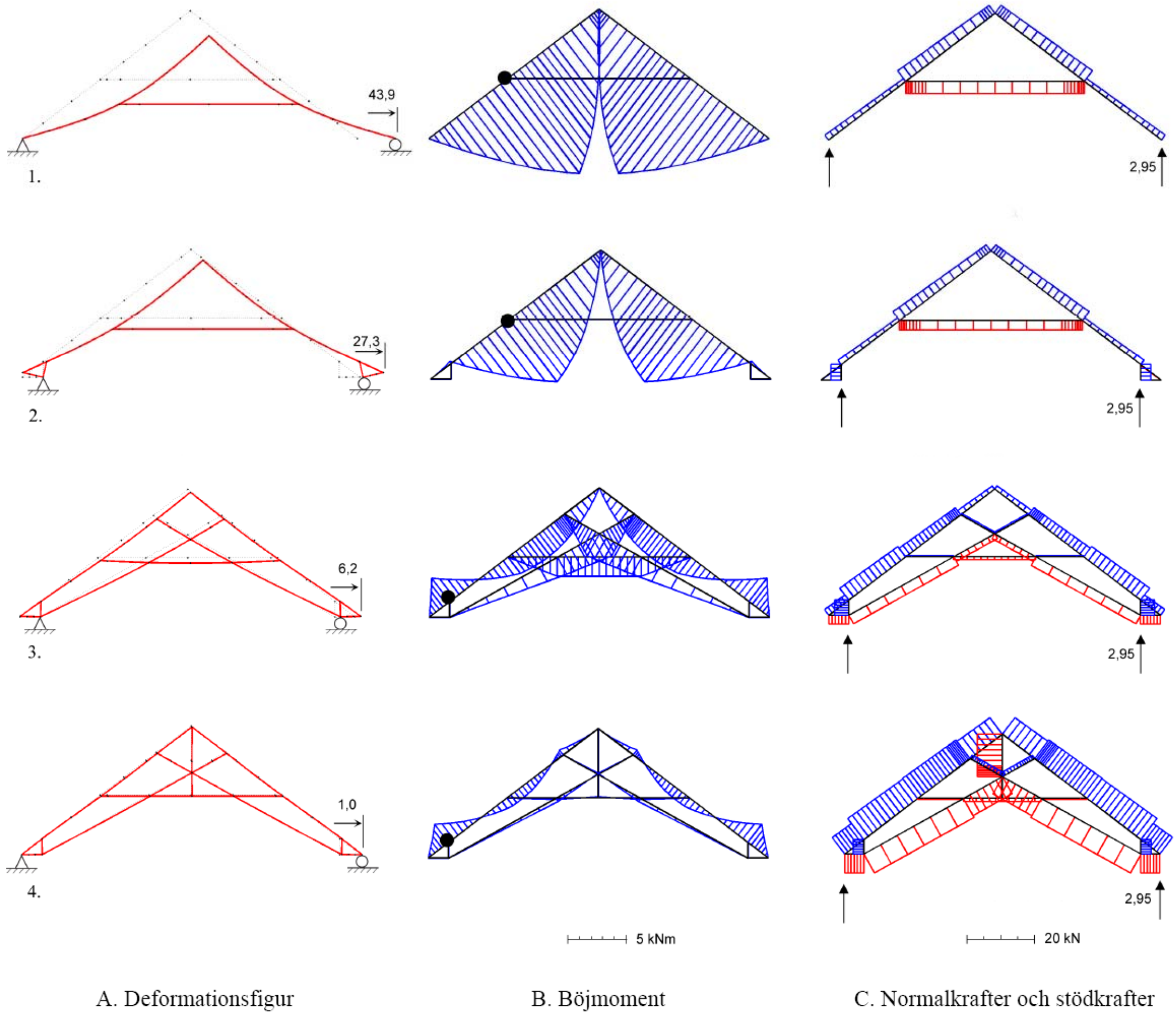


Figure 5. Roof trusses analysed for the 'task' type 'support by compression and tension' from Sandin [1]. To the left deflections, in the middle bending moments, and to the right normal and reaction forces

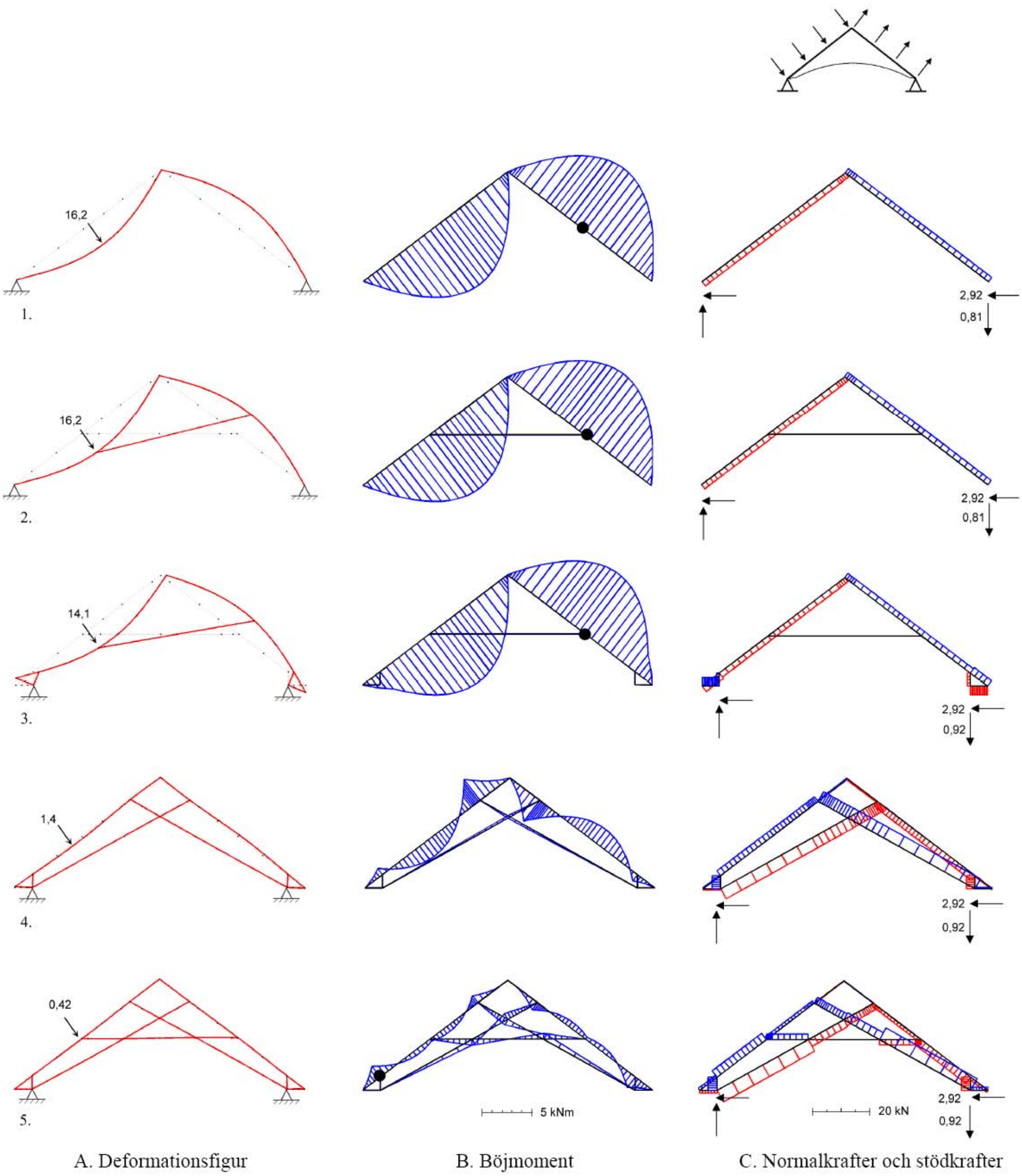


Figure 6. Roof trusses analysed for the 'task' type 'support as two beams' from Sandin [1]. To the left deflections, in the middle bending moments, and to the right normal and reaction forces

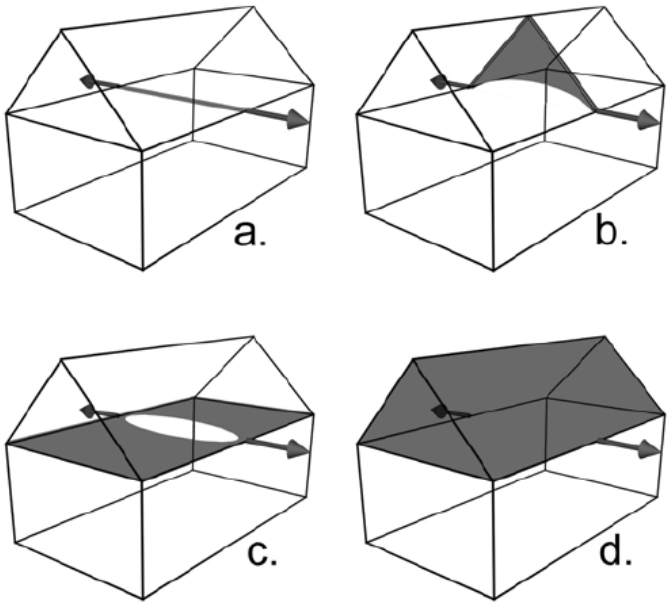


Figure 7. Space occupied by load-carrying structures

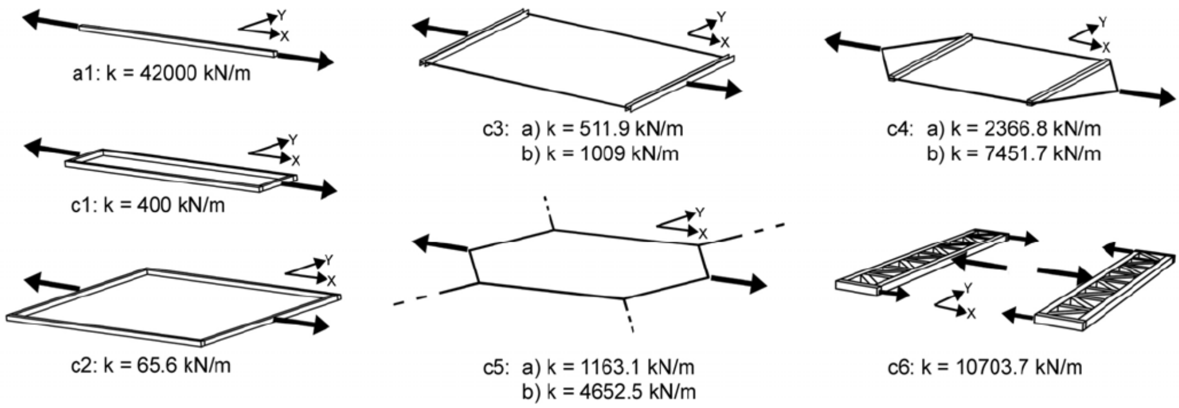


Figure 8. Stiffness that differing forms of horizontal support provide

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