Computational Mechanics for Advanced Timber Engineering

- from material modeling to structural applications -

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Wood products for structural elements are gaining importance in the building sector. Not least because of their evident ecological advantages, their share on the building market increases constantly, and volume consumption is facing enormous growth rates. Nevertheless, dimensioning practice and many existing design rules are still based on an empirical background, which often leads to unsatisfactory results in terms of efficiency and reliability. In order to exploit the full potential of the material and to facilitate its use for modern constructions (*figure 1*), which are characterized by two- and three dimensional bearing components, reliable computation methods for timber engineering are required.

To overcome this undesirable situation, the application of computational methods to wood, engineered wood products, and to timber connections, with the objective to provide an improved mechanical foundation for the intensification and completion of design codes in timber engineering, is forced in recent years. This is expected to boost an efficient use of wood and wood-based products in timber structures. Moreover, based on reliable design methods, new areas of applications for engineered wood products may be accessed.

Current design concepts, used in timber engineering, are characterized by:

- Deficiencies in the mechanical understanding of the clear wood behavior and its relation to microstructural characteristics, which results in a lack of knowledge of material properties for different wood species, and their dependence on wood sample-specific parameters, such as mass density and moisture content.
- Insufficient knowledge about the influence of knots, knot groups and other 'defects' on the mechanical behavior of timber elements, which makes classification of structural timber less efficient and does not allow for full utilization of the potential of the material.
- A high degree of simplification and unification of the underlying mechanical processes. As a result, important mechanical characteristics, such as plate- and lamination effects in wood products as well as the distinct compliant behavior of mechanical connections, are taken into account in a very simplified manner only. Moreover, due to a missing comprehensive mechanical concept applicable to different design tasks, empirical parameters, determined by experiments, are dominating current design concepts.

Considering these issues, the wood mechanics-related working group at the Institute for Mechanics of Materials and Structures (IMWS) at Vienna University of Technology pursues a strategy to link microstructural characteristics with mechanical properties of clear wood, which can subsequently be used for modeling of timber, of wood-based products, and of timber structural applications. This design concept is virtually applicable to all design tasks in timber engineering. In this article, the following mechanical models are presented and selected results are given to illustrate the potential of the integrative approach:

- A multi-scale model for wood developed within the framework of continuum micromechanics, which is able to provide clear wood properties as a function of wood species, mass density, moisture content, and other parameters related to the wood microstructure. This model serves as supplier of clear wood properties for all subsequent mechanical tools.

Figure 1: *Metropol Parasol in Sevilla, Spain, one of the worlds largest timber engineering constructions with 3400 individual wooden elements*

- A 3D Finite-Element model, comprising fiber pattern and orthotropic plastic material behavior, for determining the influence of knots, knot groups and other ‘defects’ on the mechanical behavior of timber elements. This information is subsequently used for analyzing wood products.
- A 3D stochastic numerical tool to describe mechanical as well as stochastic processes and properties of wood products, such as cross-laminated and glued-laminated timber.
- A 3D Finite-Element model for analyzing dowel connections with the goal to obtain compliance functions depending on connection geometry, loading situation and possible reinforcements.

Multi-scale model for wood

Wood is a natural material with a very heterogeneous microstructure, therefore, showing a highly anisotropic and variable mechanical behavior. However, at sufficiently small length scales, universal constituents inherent in all wood species and samples as well as universal building principles can be identified [1]. These elementary biochemical components are cellulose, hemicelluloses, lignin and extractives. Together, they form a cellulose-fiber reinforced polymeric composite that builds up several layers of the cell walls of wood fibers running in stem direction. Due to the hygroscopicity of wood polymers also water is incorporated in cell walls. The characteristic cellular structure of wood is a result of an assembly of hollow wood fibers, which are up to several mm long. The annual ring structure, typical for temperate softwood and visible to the naked eye, arises from a gradual transition from thin-walled earlywood cells to thick-walled latewood cells, which is formed during one growth season. In hardwood, additionally high amounts of ray cells running in radial direction from pith to bark and larger-sized fibers so-called vessels are present. Characteristic length scales of softwood are illustrated in *figure 2.*

The composition of constituents, their shape and distribution within a micro-heterogeneous material, as well as their mechanical properties and their interaction between each other, govern the mechanical properties at the macroscale. Hence, micromechanical approaches aim at formulating the relationship between microstructure and effective or so-called macro-homogeneous mechanical properties at higher length scales. Doing this in a repetitive manner, multi-scale models representing the hierarchical microstructure of clear wood without growth irregularities can be developed (*figure 2*). At each length scale, so-called representative volume elements or repetitive unit cells are suitably chosen to represent the actually diverse microstructure in a statistically representative manner. As regards micromechanical methods, continuum micromechanical approaches such as the Mori Tanka method and the self-consistent scheme are used in combination with the Unit Cell method and laminate theory.

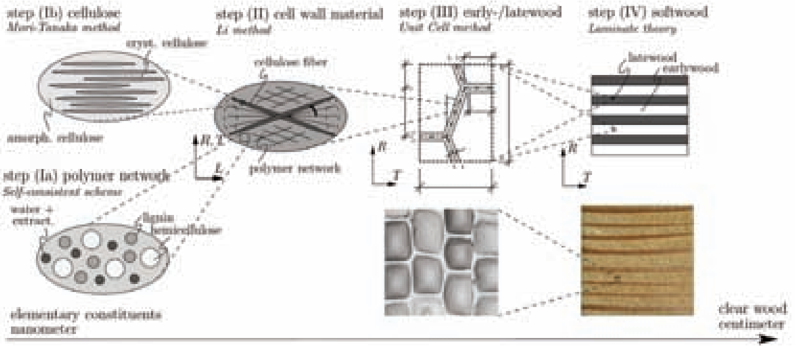
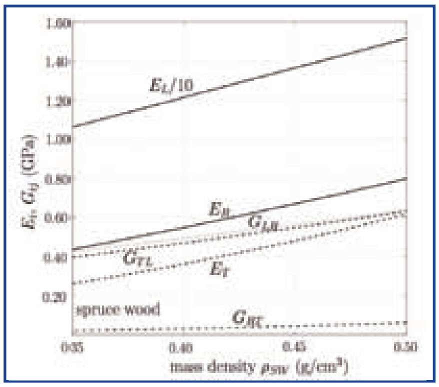


Figure 2:
Hierarchical microstructure of softwood and its representation in a multi-scale micromechanical model

Since 2005, at the Institute for Mechanics of Materials and Structures, micromechanical models for elastic properties [2,3], elastic limit stresses (as a measure for strength) [4], hygro-expansion characteristics [5], and viscoelastic properties [6] of clear wood have been developed. These models have been applied to different wood species (softwood and hardwood) as well as to deteriorated (fungal degradation) and archaeological wood. In all these applications, comparisons with experimental results at different length scales underline the suitability and the predictive capability of the developed models.

The great benefit of such a modeling strategy, combining micromechanics with multiscale observations, is that macroscopic variations in mechanical properties can be related to microstructural fluctuations. Consequently, microstructural characteristics for a better prediction of mechanical properties of clear wood can be identified. Moreover, the anisotropic behavior of wood requires a considerable effort for experimental characterization of material properties, which can be overcome by using micromechanical models in combination with microstructural characterization techniques. Exemplarily, the model-predicted influence of changing mass density on orthotropic Young’s moduli and shear moduli of spruce wood are illustrated in *figure 3*. This is for instance used as input to numerical simulation tools for timber,

Figure 3:
Influence of mass density on Young’s moduli E_L, E_R, E_T and shear moduli G_{LR}, G_{TL}, G_{RT} of spruce wood (with respect to the longitudinal (L), radial (R), and tangential (T) direction).



for engineered wood products, and for dowel connections in wood, presented in the following sections.

Finite-Element model for timber elements

Continuing with the multi-scale strategy as proposed for clear wood in the previous section, at the next higher observation scale, timber elements are considered. Doing this, it becomes obvious that wood is a naturally grown material, with inhomogeneities like knots and other growth-induced 'defects'. These cause fiber deviations and, thus, significant stiffness and strength reductions in their vicinities due to the orthotropic material characteristics of wood. This is the reason why timber is typically subjected to grading processes, in order to cut out sections, which contain critical knots, and to categorize the remaining logs. Various mechanical and visual grading methods exist, where the influence of knots on the effective bending strength is roughly estimated either on experimentally obtained stiffness values or through surface information from optical measurements (cameras or lasers). Both grading techniques are not able to take the 3D morphology of knots and the resulting fiber deviations appropriately into account. Moreover, no mechanically based prediction about the influence of the knot volume, arrangement and position on certain effective strength values can be made.

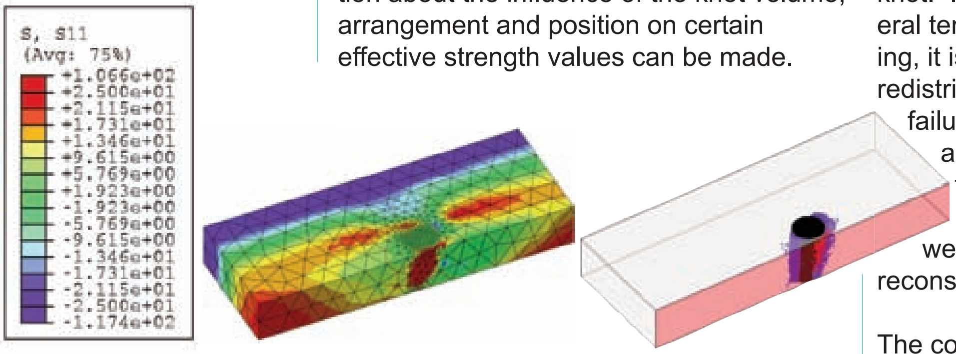


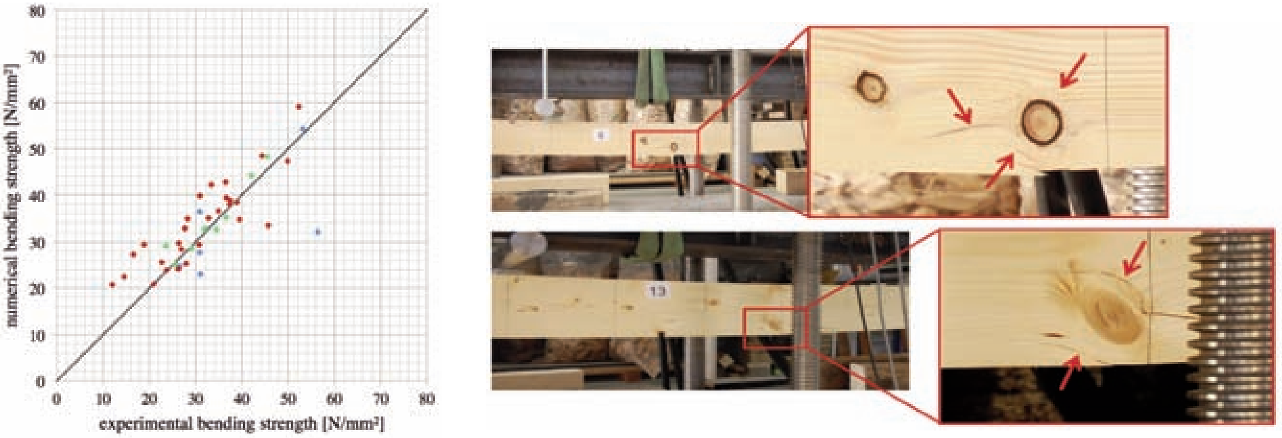
Figure 4: *Section of the 3D Finite-Element model for timber elements with knots and normal stress S11 in longitudinal direction (left), and areas of lateral-tension failure (blue) in the vicinity of a knot (right)*

For this purpose, a numerical simulation tool based on the Finite-Element method (*figure 4*) has been developed at the IMWS, in recent years [7], which enables a 3D virtual reconstruction of timber elements, including all growth- and production-induced 'defects'. The tool is based on a geometrical model, which allows for the description of the 3D fiber course [8] in the vicinity of knots, modeled as rotationally symmetric cones. The elastic behavior of the clear wood, with respect to principal material directions, is obtained from the micromechanical model presented in the section before. In each integration point, failure is described according to the orthotropic criterion of Tsai and Wu [9], and strains are following an associated flow rule in the plastic range.

Experimental observations have shown that structural failure of timber is mainly characterized by brittle failure modes (*figure 5*), which are initiated in areas where lateral-tension stress states appear/dominate. This is the case either around knots, due to strong fiber deviations, or at capped fibers at the surfaces of wooden boards. Within the presented numerical tool, start of structural failure is assessed, by analyzing the stress states in the vicinity of each knot. If the 'plastified' volume due to lateral tension around a knot starts decreasing, it is assumed that global stress redistribution takes place and structural failure occurs. The accuracy of this approach is evaluated by means of four-point bending tests, where 32 boards with different cross-sections were loaded up to failure and manually reconstructed for numerical analyses.

The comparison between the experimentally and numerically obtained bending strengths is shown in *figure 5*. Basically, the bending strengths obtained with the numerical simulation tool agree well with the experimental results. Deviations arise

Figure 5: *Comparison of experimentally and numerically obtained bending strengths of timber elements (left), and failure modes around knots due to lateral tension (right)*



for beam samples with very high density and/or when the main failure mechanism is triggered by capped fibers in the tensile zone. The consideration of these effects within this simulation tool is a current research focus at the IMWS.

Stochastic approach for wood products

Research on the mechanical behavior of wood products (glued-laminated timber, GLT, and cross-laminated timber, CLT) has mainly been performed experimentally so far. In general, comprehensive test series were carried out and the results were analyzed statistically in order to identify the relation between the distribution of mechanical properties of the laminations and corresponding characteristics of the wood product. Following this approach, only limited insight into the homogenization effects in wood products is gained. In particular, no separation of mechanical and stochastic effects is possible.

In order to obtain enhanced insight, the experimental approaches were complemented by analytical or numerical investigations. The former are mainly based on application of stochastic concepts to mixed parallel-serial systems. Previous numerical approaches mostly use the Finite-Element method to study the internal load transfer and apply a Monte Carlo approach to capture the stochastic character of the problem (see, for example [10]). The high computational effort of such an stochastic scheme allows a very small number of stochastic variables only. Furthermore, it does not indicate the sensitivity of mechanically relevant parameters on the stochastic result. For this reason, more advanced stochastic methods need to be investigated in terms of the applicability to wood-based products [11].

In general, a Stochastic Finite-Element approach can be divided into three parts: (i) the approximation of so-called realizations of the considered stochastic variables with a random process model, (ii) the discretization of the random process/stochastic field, and (iii) the implementation into a Finite-Element Method where the mechanical and stochastic problem is coupled. Considering glued-laminated timber elements, the mass density distribution in longitudinal direction is modeled as a linear random process, while for the distribution of the elastic properties a discontinuous model is used (*figure 6(a)*). The discontinuous random process is defined through information from an optical scanning device (WoodEye) and effective stiffness properties of different knot groups from the Finite-Element method for timber elements, presented in the section before. Various methods exist for the discretization of the stochastic field. In *figure 6(b)* a spatial discretization, in analogy to the discretization of the mechanical problem, and a discretization using a serial expansion (Karhunen-Loève) are exemplarily shown for the elastic modulus in longitudinal direction of a 4-layered GLT beam. These discretization methods were implemented into two different 'closed' Stochastic Finite-Element formulations, (i) the perturbation method, where the stochastic system matrix and the response vector are expressed as Taylor series expansions, and (ii) a spectral approach, where the stochastic part of the system matrix is written as a sum of certain 'basis functions'. The application of these methods to a glue-laminated timber element has shown that both methods are able to capture important effects, such as lamination effects, and deliver appropriate effective stochastic information (*figure 6(c)*) [11], similar to the Monte-Carlo simulation, but with a smaller computational effort. This allows for a stochastic analysis of wood products with a high resolution of the stochastic as well as mechanical conditions.

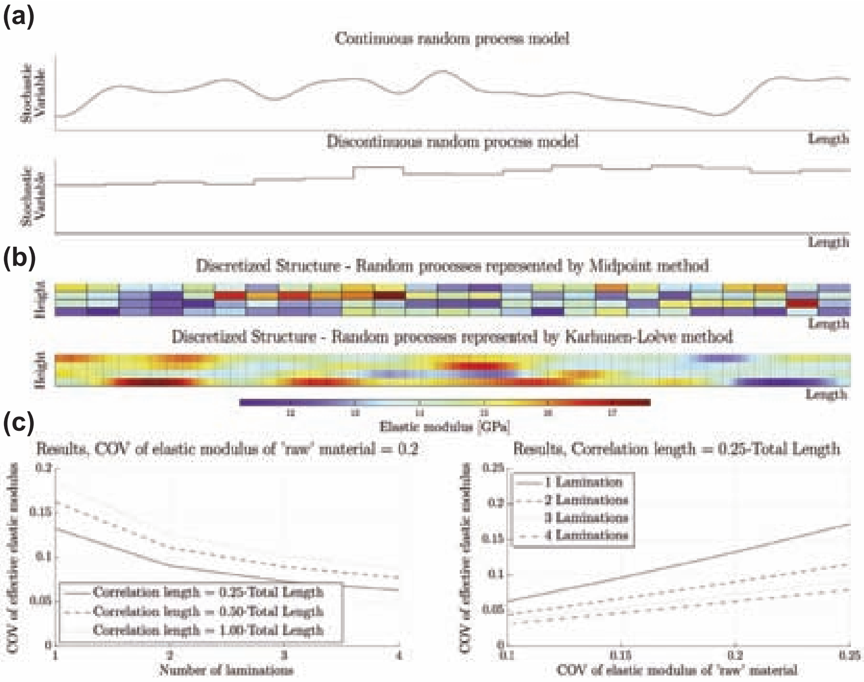


Figure 6:
(a) Random process models for property fluctuations in longitudinal direction of wooden lamellas,
(b) illustration of two different discretization methods of the stochastic field of a 4-layered glued-laminated timber element, and
(c) influence of the number of laminations and the 'raw' material on the coefficient of variation (COV) of the effective elastic modulus in longitudinal direction of a glued-laminated timber element.

Finite-Element model for dowel connections

Steel dowel connections are commonly used in timber structures since they can transfer and withstand very high loads between structural members. Their mechanical behavior is mainly based on

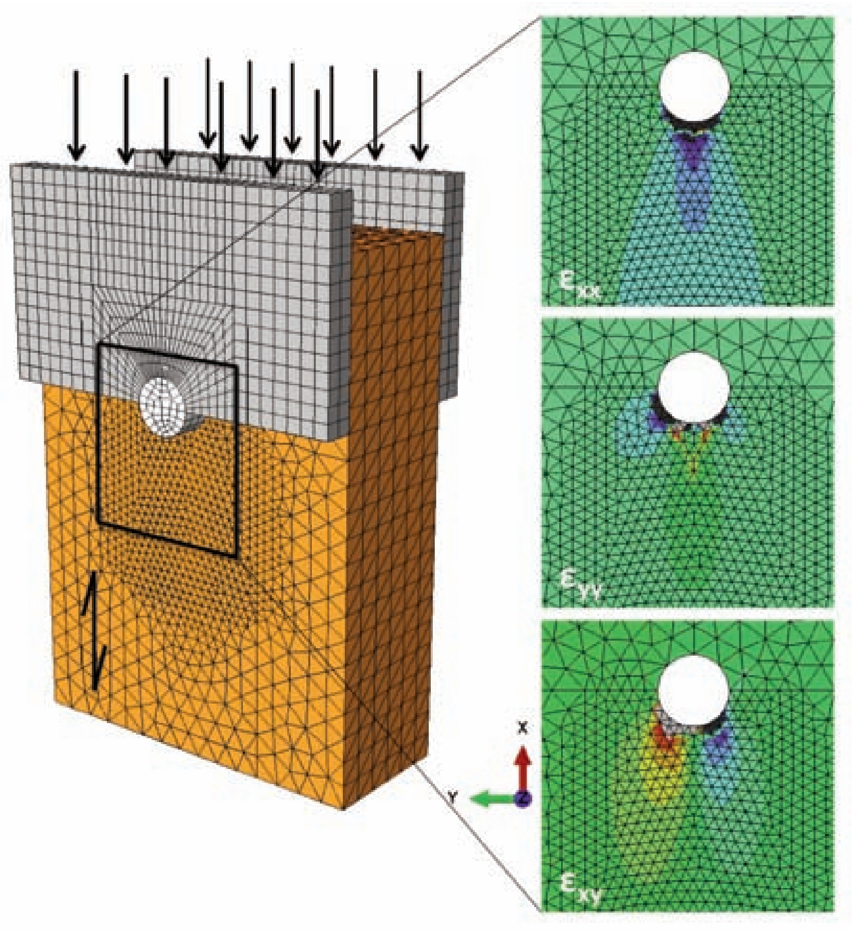


Figure 7:
Simulation of embedment tests (left) with wood loaded in fiber direction (parallel to the x-direction) through steel plates and steel dowel with corresponding strain fields (right) on the wood surface

the interaction between stiff steel dowels and the wooden parts, which further depends on the geometry of the connection and the loading direction. Due to the cylindrical shape of the dowels and the anisotropic behavior of wood, the stress and strain field in the wood around the dowel is very heterogeneous and encompasses stresses perpendicular to the loading direction and shear stresses in addition to compressive stresses in loading direction. Furthermore, due to stress concentrations close to the dowel, non-reversible deformations occur very localized at higher load levels. As a result, a ductile overall behavior of the connection is observed as long as splitting of wood due to stresses perpendicular to the grain is not decisive or prevented by means of lateral reinforcement. Other possible failure modes are related to shear failure under a single dowel or a dowel group (block-shear failure). In case of slender dowels, the load bearing capacity is additionally influenced by material properties of the steel dowel since plastic hinges may evolve before ultimate failure. The consideration of the compliant behavior of dowel connections is of importance for the analysis of timber structures, because it may strongly influence the redistribution of internal loads and subsequently the global deformations of timber structures.

In order to overcome current limitations and simplifications of design equations in standards, we aim at gaining increased insight into the load transfer in dowel connections. This will be the basis for the prediction of ultimate loads of arbitrary configurations of dowel connections with consistent deformation characteristics. Therefore, a numerical simulation tool for dowel connections has been developed [12]. It encompasses an anisotropic elasto-plastic material model for wood, which is based on micromechanical predictions from the presented multi-scale model for clear wood. To the clear wood sections a Tsai-Wu failure criterion with an associated plastic flow rule is assigned. Through a contact model, the compliant behavior at the interface between the steel dowel and the wood borehole surface in normal (non-linear pressure-overclosure relationship) and tangential (friction) direction, is taken into account.

The numerical simulation tool was applied to single-dowel connections as well as to dowel embedment tests (*figure 7*) with different configurations related to material properties and geometry. Finite Element calculations were compared to experimental data. This shows that the model is particularly suitable for the study of the deformations of connections up to the serviceability limit, where the contact behavior considerably influences the deformation characteristics. Additionally, strain fields in steel to wood embedment tests were measured by means of a Digital Image Correlation system and used for a comparison with model predictions.

Based on these findings, more complex loading conditions and connection configurations can be studied. A future extension of the model concerns brittle failure of connections due to tensile stresses perpendicular to the grain or shear stresses, where fracture mechanics approaches will be applied.

Summary and conclusions

In this article, mechanical methods for advanced timber engineering, aiming at an improved understanding of the mechanical processes from the material scale up to structural applications, are presented. At the clear wood scale, a continuum micromechanics based multi-scale model gives access to microstructural-function relationships, i.e. it links microstructural characteristics such as mass density and moisture content with effective clear wood properties. This information is subsequently used in 3D numerical simulation tools for timber and dowel connections. The former allows for determining the influence of knots on the effective stiffness and strength of timber, while the latter gives insight into the stress-/ and deformation states within dowel joints and can be used to obtain global compliance functions for different connection geometries. Furthermore, the obtained effective stiffness behavior of timber elements with certain knot groups, together with information about the knot distribution and configuration within wooden boards from optical scanning devices, serve as input to stochastic Finite-Element approaches for wood-based products. The combination of a mechanical description, which is able to adequately take stress transfer between lamellas into account, with stochastic approaches makes it possible to assess probability distributions for effective material parameters of wood products, based on stochastic information of the 'raw' material (wooden lamellas).

In conclusion, computational mechanical methods applied to wood, wood products, and structural components of timber structures provide enhanced insight into load-transfer characteristics from the material level up to structural applications. The integrative use of the developed tools ensures reliable input data for subsequent numerical models. Continuous refinement of each tool, utilization of interactions, and exploitation of synergies between them, accompanied by thorough experimental validations, will finally lead to a comprehensive analysis tool, which can serve as a profound basis for design concepts in timber engineering. ●

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