Dynamic effects in reinforced timber beams at time of timber fracture

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1 Introduction

In reinforced timber beams, the moment of brittle failure, i.e. the transition from the unfractured to the fractured state, is characterized by dynamic effects. In the unfractured state, the stresses under consideration are transferred proportionally by the timber beam and the reinforcement. Brittle failure in the timber results in associated stress release in the beam. The reinforcement is activated to carry the released stresses by deformations between the beam and the reinforcement. This sudden process leads to dynamic impact, resulting in additional stresses in the system. To receive an idea about the corresponding effects, a simple model is presented.

2 Method

To evaluate this situation, a spring-mass system can be used, see Fig. 2.1. In the unfractured state, the spring stiffness is given by the relevant stiffness of the timber beam k_{timber} (e.g. perpendicular to grain stiffness or shear stiffness) and the additional stiffness of the reinforcement embedded in the timber k_{reinf}. From the moment of brittle failure of the timber, the force has to be solely carried by the spring representing the reinforcement. Due to the reduction of total spring stiffness, the system falls from its original position into its new position of equilibrium. The magnitude of deformations is dependent on the proportion of force and spring stiffness before and after fracture. The system is in vibration, the maximum amplitude is double the static deformation between the original position and the new position of equilibrium. The vibration can be damped by either an activation of friction (k_{μ}) in the fracture plane (e.g. in the case of shear fracture) and/or by the plastic deformation of the reinforcement. See Fig. 2.1.

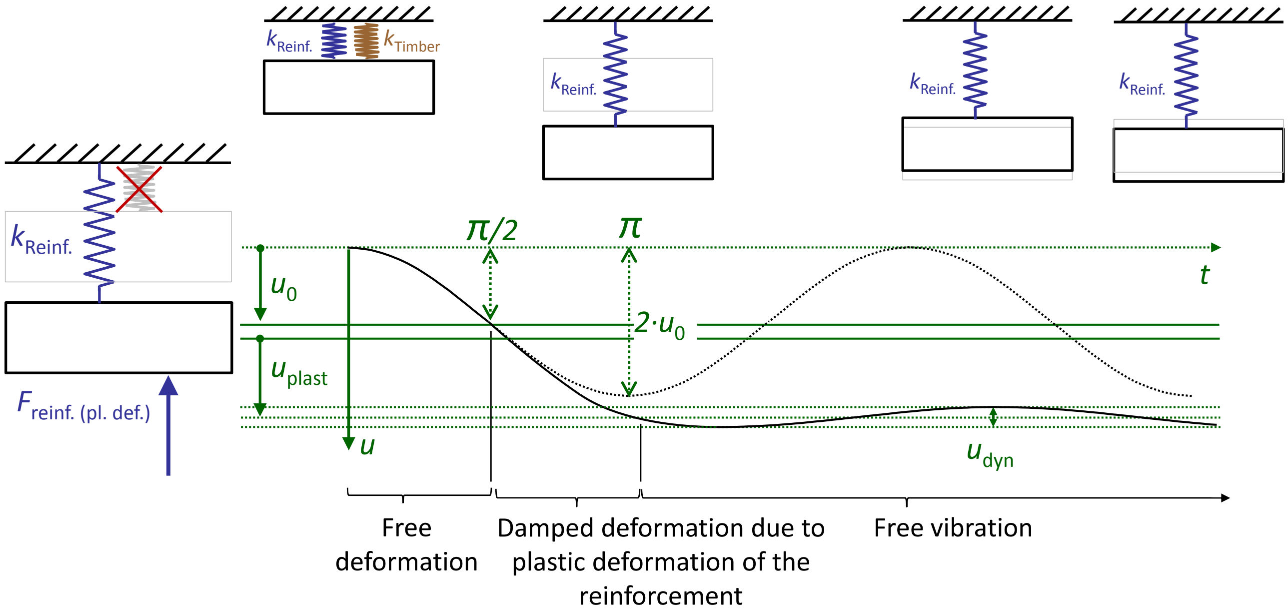

Figure 2.1. Spring-mass-system after timber fracture: free undamped vibration incl. static deformation u_0 between initial position and new position of rest and the dynamic deformation; dissipation of energy through plastic deformation u_{plast} of the reinforcement.

The following explanations concerning the sequence and influencing factors at the time of fracture are given on the basis of a load-deformation diagram that is combined with a time-deformation diagram, as shown in Fig. 2.2. This representation is based on comparable considerations in an unpublished expertise. The following discussion is based on the numbered sequence given in Fig 2.2. The values given are based on the assumption of a pure brittle failure over the full beam length and disregarding potentially higher properties during impact.

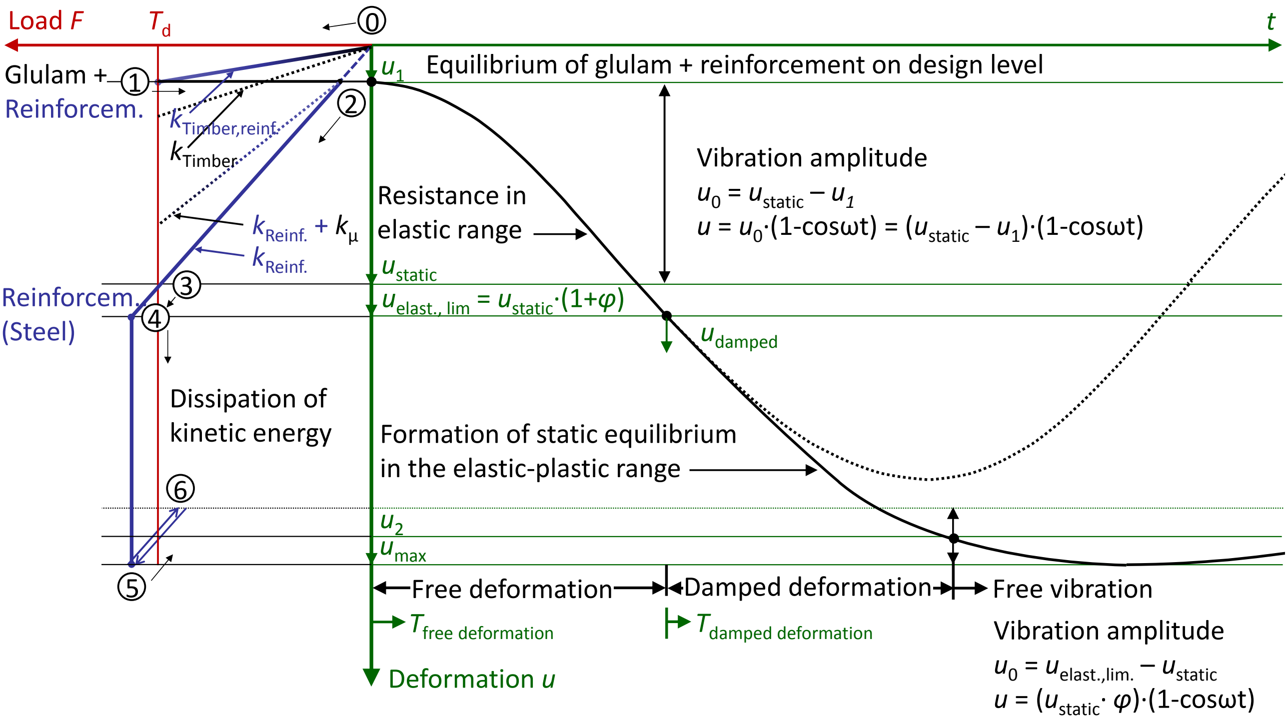

Figure 2.2. Schematic of the processes at the transition from the unfractured state (equilibrium, static position of rest u_1) to the fractured state (equilibrium, static position of rest u_2).

0. The beam is not loaded. Increasing load will lead to increasing deformation. These are smaller in the case of a reinforced beam compared to an unreinforced beam.

1. The load has reached the resistance of the rigid composite beam. The deformation u_1 is dependent on the stiffness of the timber beam and the embedded reinforcement. The exceedance of the design situation results in a sudden, brittle timber failure in the timber cross-section.

2. The elimination of the stiffness of the timber beam in the fracture plane results in a lower stiffness of the interconnection between the now mechanically jointed parts of the composite beam. The stresses that were proportionally transferred by the timber and the reinforcement are now solely transferred by the latter. The activation of the resistance of the reinforcement results in additional deformation. Another potential mechanism to transfer the released stresses is friction, which is activated in the case of shear stresses interacting with compression stresses perpendicular to the grain. Due to the high uncertainty of the friction coefficients, this mechanism is mostly neglected in structural design.

3. The system falls from its original state of equilibrium into the new position of equilibrium whereby it is restrained by the elastic deformation of the reinforcement. In the case of free vibration, i.e. elastic deformation of the reinforcement without energy dissipation, the maximum amplitude would be double the static deformation between the original and the new position of equilibrium (u_{static} - u_1). A corresponding design would result in a considerable increase in necessary capacity of the reinforcement. In [1] it is shown that, in the case of shear reinforcement, the load-carrying capacity of the interconnection would have to be increased by 60 % - 80 %, compared to a pure static design.

4. Another possible approach is to take into account the dissipation of kinetic energy by the plastic deformation of the reinforcement. The limit deformation $u_{\text{elast.,lim.}}$, at which a transition from elastic to plastic deformation is acceptable, should have a safe distance from the static position of rest, u_{static}. The relationship between both deformations can be expressed by an increase factor φ ($u_{\text{elast.,lim.}} = u_{\text{static}} \cdot (1+ \varphi)$). Static equilibrium is established in the elastic-plastic range.

5. The plastic deformation of the reinforcement ends when all kinetic energy is dissipated. The area defined by the resistance of the reinforcement during plastic deformation and the load in the fracture plane equals the dissipated kinetic energy. The larger the difference between resistance and load, the lower the necessary plastic deformation. The maximum deformation u_{max} can be expressed as a function of the static deformation in the unfractured state, u_1, the new position of equilibrium, u_{stat}, and the increase factor φ, as follows (a derivation can be found in [1]).

$$u_{max} = u_{static} \cdot \left\{(1+\varphi) + \frac{((1-u_1/u_{static})^2-\varphi^2)}{2\cdot\varphi}\right\} \tag{1}$$

If the capacity for plastic deformation of the reinforcement is known, the minimum necessary increase factor φ can be determined with Eq. (1).

6. After the damped movement, a free movement around the new static position of equilibrium, u_2, is reached. The vibration amplitude is $u_{static} \cdot \varphi$, equaling the proportion of the elastic deformation, exceeding the static position of rest (u_{stat}).

By increasing the ratio of deformations (u_1/u_{static}) through the stiffness ratio ($k_{Reinf.}/k_{Timber,Reinf.}$) before and after fracture, the magnitude of vibration amplitude u_0 and thus the magnitude of kinetic energy to be dissipated, is reduced. Here, bonded-in reinforcement has some advantage over screwed-in reinforcement, due to its higher withdrawal stiffness. The same effect can be reached by an increase of reinforcing elements.

An important parameter is the ductility of the reinforcement. An increase in plastic deformation capacity is synonymous with a reduction in increase factor φ. Hence the necessary increase in capacity to take into account the additional load from dynamic effects will reduce. Most reinforcing elements used in modern timber structures are optimized for high axial capacity which involves a reduction of ductility of the (high-strength) steel cross-section. Comparative calculations indicate that rather low ductility is necessary to reach a considerable reduction in the increase factor φ. Comparative calculations on shear reinforcement reported in [1] show that, under the assumption of a capacity of plastic deformation equal to three times the elastic deformation capacity, increase factors $0.1 \leq \varphi \leq 0.18$ (mean = 0.15) can be reached.

Self-tapping fully threaded screws that are optimized for high axial capacity feature a rather low relationship between plastic and elastic deformation capacity. Static tensile tests on typical self-tapping screws delivered values in the range of $D_s = v_u/v_y = 2.8 – 3.7$. Self-tapping screws that are less hardened or screwed-in rods feature a larger plastic deformation capacity. For the latter, relationships of $D_s = v_u/v_y = 11.8 – 14.0$ were determined.

3 References

[1] Dietsch, P. (2012): Einsatz und Berechnung von Schubverstärkungen für Brettschichtholzbauteile, Dissertation, Technische Universität München, Germany, 2012. https://mediatum.ub.tum.de/doc/1108735/1108735.pdf