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DESIGN MODEL FOR CLT PANELS REINFORCED WITH GFRP BARS

Summary: Cross laminated timber (CLT) is relatively new and eco-friendly prefabricated wood product in a form of large structural panels used mostly for floors and walls. Cross-wise layer configuration enables both in- and out-of-plane resistance of CLT panels, providing significant structural flexibility. Modern structural demands, such as long-spans and heavy loads, make additional reinforcement necessary for CLT panels in bending. Improvements can be achieved by using advanced composite materials. This paper describes a design model developed to predict load-carrying capacity and bending stiffness of CLT panels reinforced with glass fibre reinforced polymer (GFRP) bars in tension zone. Model was calibrated for unreinforced CLT panels and modified to consider the effect of GFRP reinforcement with varying reinforcement percentage. Good agreement was observed between theoretical and experimental test results for reinforced CLT panels.

Keywords: cross laminated timber, composite, FRP, theoretical analysis, capacity, stiffness

PRORAČUNSKI MODEL ZA CLT PANELE OJAČANE KOMPOZITNOM ARMATUROM

Rezime: Unakrsno lamelirano drvo *(cross laminated timber* – CLT) je relativno nov i ekološki prihvatljiv pločasti proizvod na bazi drveta u vidu panela velikih formata koji se najčešće koriste kao međuspratne konstrukcije i zidovi. Zbog međusobno unakrsno postavljenih slojeva, CLT paneli mogu biti opterećeni i u svojoj ravni i van svoje ravni, što doprinosi značajnoj konstruktivnoj fleksibilnosti. Savremeni konstruktivni zahtevi, kao što su veliki rasponi i visok intenzitet opterećenja, često zahtevaju ojačanje CLT panela izloženih savijanju van svoje ravni. Poboljšanja se mogu ostvariti korišćenjem naprednih kompozitnih materijala visokih mehaničkih karakteristika kao što su polimeri ojačani vlaknima (*fibre reinforced polymers* – FRP). U ovom radu opisan je proračunski model razvijen za predviđanje nosivosti i krutosti na savijanje CLT panela ojačanih kompozitnom armaturom u zoni zatezanja. Model je formiran tako da se može primeniti na neojačane i ojačane panele sa različitim procentom armiranja. Zabeleženo je dobro slaganje između teorijskih i eksperimentalnih rezultata za ojačane panele.

Ključne reči: unakrsno lamelirano drvo, kompozit, FRP, teorijska analiza, nosivost, krutost

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1. INTRODUCTION

Cross laminated timber (CLT) is an engineering and prefabricated wood composite product formed by adhering layers of timber boards (laminations) in an orthogonal orientation thus creating large-scale panels. As they have both in- and out-of-plane resistance, CLT panels can be used either for floors, walls, roofs or stairs. CLT single- and multi-storey buildings offer economical and environmentally friendly substitute for conventional construction materials as they reduce greenhouse gas emissions. After the end of the life cycle, CLT components can be reused, recycled or used as bioenergy, enhancing their sustainability profile [1].

Solid and glued laminated timber elements loaded in out-of-plane bending experience failure in tension zone which is usually initiated at wood defects (knots, grain deviation, resin pockets) or finger joints. This tensile failure is very brittle and difficult to predict. CLT elements are no different from this.

High-strength and high-modulus materials, such as fibre reinforced polymer (FRP) composite materials, can be used to strengthen and reinforce CLT elements in order to overcome wood defects and improve mechanical properties [2]. Reinforcement enables larger spans and higher loads that meets modern structural demands. Also, the composite effect results in enhanced exploitation of timber resource.

Developing a design model that can determine load-carrying capacity and bending stiffness of reinforced CLT panels is crucial for the optimal use of FRP reinforcement, as well as for their wider application. Reinforcement in tension zone changes the stress-strain relationship in the composite cross section. In order to describe behaviour of reinforced CLT panels as accurately as possible, the calculation model must consider non-linearity due to the plastification in timber in the compression zone.

This paper provides a design model for calculating ultimate load-carrying capacity and bending stiffness of five-layered unreinforced CLT panels and CLT panels reinforced with glass fibre reinforced polymer (GFRP) bars in tension zone with different reinforcement percentage. The calculation considers only the failure mode of CLT panels that occurred in experimental research, which is failure in tension zone. Therefore, this design model was applied to CLT panels that were experimentally tested and the results were then compared.

2. EXPERIMENTAL INVESTIGATION

Experimental investigation was conducted with the aim of determining bending behaviour of reinforced CLT panels. A total of 15 panels were tested – five unreinforced CLT panels (Series A), five CLT panels reinforced with three GFRP bars (Series B with reinforcement percentage of 0.45%) and five CLT panels reinforced with six GFRP bars (Series C with reinforcement percentage of 0.90%) in tension zone.

All CLT panels were made of softwood (spruce) classified in the strength class C24 according to EN 338 [3]. CLT panels were 440 cm long, 50 cm wide with overall thickness of 15 cm (five 3 cm thick layers with conventional orientation). GFRP bars with a nominal diameter of 12 mm were placed along the near-surface grooves that were cut into panels along their entire length. Epoxy adhesive was used to bond GFRP bars. In that way, reinforcement was hidden and protected by the surrounding wood.

Panels were tested in four-point bending configuration as simply supported beams with a span of 420 cm symmetrically loaded with two concentrated forces at a distance of 90 cm, in accordance with EN 16351 [4]. Dimensions of CLT panels and testing layout are presented in Fig. 1.

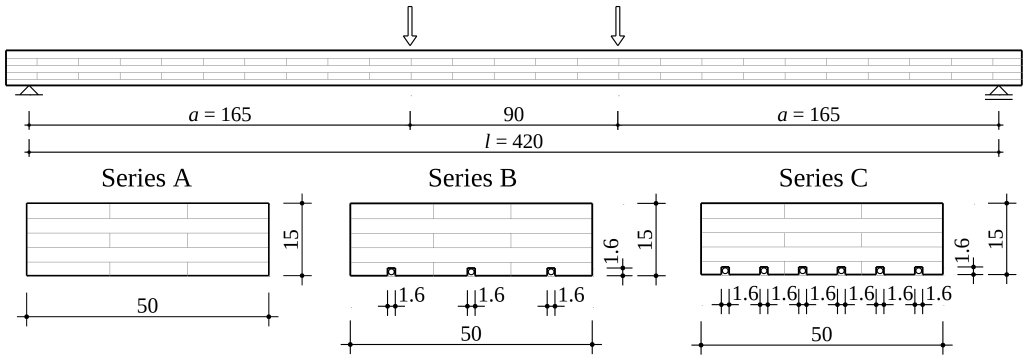

Figure 1: Test configuration of CLT panels

Experimental test results are presented together with the theoretical results in the following sections of the paper.

3. THEORETICAL MODEL

3.1. CONSTITUTIVE RELATIONS FOR MATERIALS

The analysis of nonlinear behaviour of reinforced CLT panels in out-of-plane bending requires the definition of stress-strain relationship for wood under tension and compression (parallel to grain). Generally, there are different constitutive models regarding compression that describe behaviour of wood with varying degrees of approximation as presented in Fig. 2 [5]. Model 1 is the most realistic one, but also the most complex to incorporate into design model. Nevertheless, the idealised model 3 (linear-elastic in tension and linear-elastic-perfectly plastic in compression) can also be implemented with sufficient accuracy.

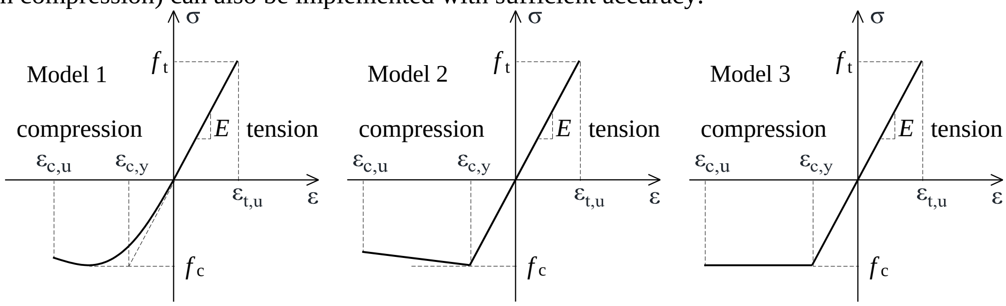

Figure 2: Constitutive models for timber

GFRP material can be idealised with linear-elastic constitutive model with a brittle failure.

3.2. CALCULATION OF LOAD-CARRYING CAPACITY

Design models should take into account the actual behaviour of materials which can be confirmed by research or experimental testing. A theoretical model has been developed to predict the behaviour of CLT panels reinforced with GFRP bars and to calculate their load-carrying capacity. The basic assumptions and simplifications of the adopted model were:

- plain cross-section remains plain during deformation,
- bond between CLT and GFRP is ideal,
- elastic properties of epoxy adhesive are not considered,
- behaviour of wood in tension is linear-elastic and in compression linear-elastic-perfectly plastic (model 3 in Fig. 2),

- behaviour of GFRP bars in tension is linear-elastic,
- the impact of cross-section weakening due to plastification is neglected.

The calculation determines bending moment in the most loaded cross-section of the CLT element for a specific level of strain of wood fibres in tension. Based on the calculated value of the bending moment, the value of load can be further calculated.

Experimental tests have shown that the failure mechanism of both unreinforced and reinforced CLT panels is brittle failure in the tension zone, with or without visible partial plastification in the compression zone. Wood behaves in a linear-elastic manner until it reaches the yielding strain at the upper edge of the cross-section before reaching the ultimate tensile stress. As defined by the constitutive model, when strains in compression exceed the limit of elasticity, plastification occurs and stress in compression can no longer be increased. This causes the shifting of neutral axis so that equilibrium conditions are satisfied. The behaviour of CLT panels in this phase is plastic until failure occurs, which happens upon reaching the value of ultimate tensile stress at the lower edge of the cross-section. Depending on the reinforcement percentage, other failure modes are also possible, e.g. failure occurs beforehand due to reaching the limiting value of compressive strain at the upper edge of the cross-section. However, this is not observed in the experimental testing.

Idealised distribution of strains and stresses of five-layered CLT panel with cross-section width *b* and height *h*, reinforced with GFRP bars in tension zone, is presented in Fig. 3.

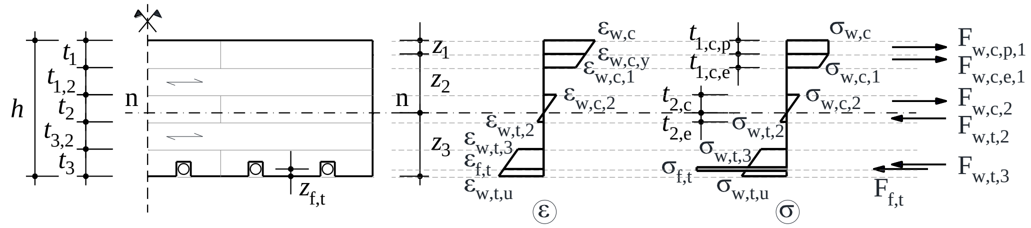

Figure 3: Stress and strain distribution in CLT cross-section

Knowing the ultimate strains $\varepsilon_{w,t,u}$ and $\varepsilon_{w,c,y}$, other characteristic strains in the cross-section (Fig. 3) can be determined from the compatibility conditions:

$$\begin{cases} \varepsilon_{w,c,1} = \dfrac{z_1 + z_2 - t_1}{z_2} \cdot \varepsilon_{w,c,y} \\ \varepsilon_{w,c,2} = \dfrac{t_{2,c}}{z_2} \cdot \varepsilon_{w,c,y} \\ \varepsilon_{w,t,2} = \dfrac{t_{2,t}}{z_3} \cdot \varepsilon_{w,t,u} \\ \varepsilon_{w,t,3} = \dfrac{z_3 - t_3}{z_3} \cdot \varepsilon_{w,t,u} \\ \varepsilon_{f,t} = \dfrac{z_3 - z_{f,t}}{z_3} \cdot \varepsilon_{w,t,u} \end{cases} \quad (1)$$

with the following relations:

$$\begin{cases} z_1 = t_{1,c,p} = h - z_2 - z_3 \\ z_2 = \varepsilon_{w,c,y} / \varepsilon_{w,t,u} \cdot z_3 \\ t_{1,c,e} = t_1 - z_1 \\ t_{2,c} = h - z_3 - t_1 - t_{1,2} \\ t_{2,t} = z_3 - t_3 - t_{3,2} \end{cases} \quad (2)$$

where:
t_i is thickness of the i-th longitudinal layer,
$t_{i,2}$ is thickness of cross layer next to the i-th longitudinal layer, and
$z_{\mathrm{f,t}}$ is distance between the centre point of GFRP bars in tension zone and bottom edge of CLT panel.

For given values of strains, corresponding values of stresses in the cross-section (Fig. 3) can be calculated according to the specified stress-strain relations:

$$\begin{cases} \sigma_{\mathrm{w,c}} = \varepsilon_{\mathrm{w,c,y}} \cdot E_{\mathrm{w}} = f_{\mathrm{c}} \\ \sigma_{\mathrm{w,c,1}} = \varepsilon_{\mathrm{w,c,1}} \cdot E_{\mathrm{w}} \\ \sigma_{\mathrm{w,c,2}} = \varepsilon_{\mathrm{w,c,2}} \cdot E_{\mathrm{w}} \\ \sigma_{\mathrm{w,t,2}} = \varepsilon_{\mathrm{w,t,2}} \cdot E_{\mathrm{w}} \\ \sigma_{\mathrm{w,t,3}} = \varepsilon_{\mathrm{w,t,3}} \cdot E_{\mathrm{w}} \\ \sigma_{\mathrm{w,t,u}} = \varepsilon_{\mathrm{w,t,u}} \cdot E_{\mathrm{w}} = f_{\mathrm{t}} \\ \sigma_{\mathrm{f,t}} = \varepsilon_{\mathrm{f,t}} \cdot E_{\mathrm{f}} \end{cases} \tag{3}$$

where:
E_{w} is modulus of elasticity parallel to the grain of CLT panel, and
E_{f} is modulus of elasticity of GFRP bars.

The position of the neutral axis (unknown z_3) is determined from the equilibrium equations of internal forces in the longitudinal axis direction (in accordance with the stress distribution in CLT cross-section in Fig. 3):

$$F_{\mathrm{w,c,p,1}} + F_{\mathrm{w,c,e,1}} + F_{\mathrm{w,c,2}} = F_{\mathrm{w,t,3}} + F_{\mathrm{w,t,2}} + F_{\mathrm{f,t}} \tag{4}$$

with the following internal forces:

$$\begin{cases} F_{\mathrm{w,c,p,1}} = \sigma_{\mathrm{w,c}} \cdot t_{\mathrm{1,c,p}} \cdot b \\ F_{\mathrm{w,c,e,1}} = \dfrac{\sigma_{\mathrm{w,c,1}} + \sigma_{\mathrm{w,c}}}{2} \cdot t_{\mathrm{1,c,e}} \cdot b \\ F_{\mathrm{w,c,2}} = \dfrac{\sigma_{\mathrm{w,c,2}}}{2} \cdot t_{\mathrm{2,c}} \cdot b \\ F_{\mathrm{w,t,2}} = \dfrac{\sigma_{\mathrm{w,t,2}}}{2} \cdot t_{\mathrm{2,t}} \cdot b \\ F_{\mathrm{w,t,3}} = \dfrac{\sigma_{\mathrm{w,t,3}} + \sigma_{\mathrm{w,t,u}}}{2} \cdot t_3 \cdot b \\ F_{\mathrm{f,t}} = \sigma_{\mathrm{f,t}} \cdot A_{\mathrm{f,t}} \end{cases} \tag{5}$$

where:
$A_{\mathrm{f,t}}$ is cross-section area of GFRP bars in tension zone.

The resulting bending moment (moment capacity) M_{u} can be calculated as the sum of the moments of internal forces about the neutral axis:

$$\begin{aligned} M_{\mathrm{u}} = {} & F_{\mathrm{w,c,p,1}} \cdot \left(z_2 + \frac{z_1}{2} \right) + F_{\mathrm{w,c,e,1}} \cdot \left(z_2 - \frac{t_{\mathrm{1,c,e}}}{3} \cdot \frac{2\sigma_{\mathrm{w,c,1}} + \sigma_{\mathrm{w,c}}}{\sigma_{\mathrm{w,c,1}} + \sigma_{\mathrm{w,c}}} \right) + F_{\mathrm{w,c,2}} \cdot \left(\frac{2}{3} \cdot t_{\mathrm{2,c}} \right) + \\ & + F_{\mathrm{w,t,2}} \cdot \left(\frac{2}{3} \cdot t_{\mathrm{2,t}} \right) + F_{\mathrm{w,t,3}} \cdot \left(z_3 - \frac{t_3}{3} \cdot \frac{\sigma_{\mathrm{w,t,u}} + 2\sigma_{\mathrm{w,t,3}}}{\sigma_{\mathrm{w,t,u}} + \sigma_{\mathrm{w,t,3}}} \right) + F_{\mathrm{f,t}} \cdot \left(z_3 - z_{\mathrm{f,t}} \right) \end{aligned} \tag{6}$$

Based on the calculated value of moment capacity and test configuration of CLT panels with a shear span *a* presented in Fig. 1, the value of load-carrying capacity can be further calculated:

$$F_{\max} = \frac{2 \cdot M_{\mathrm{u}}}{a} \tag{7}$$

3.3. CALCULATION OF BENDING STIFFNESS

Bending properties of CLT panels for serviceability limit state must consider shear flexibility of transverse layers by using the effective bending stiffness. So far, there are three analytical methods for calculating the effective bending stiffness of CLT panels and the most conventional one is the Gamma method. Current European Technical Approvals (ETA) have adopted this method that is shown in Annex B of Eurocode 5 [6] with certain changes to the original theory. The main assumptions for applying this method are:

- CLT panels are simply supported and loaded perpendicular to their plane,
- CLT panels carry load only in longitudinal direction,
- only longitudinal layers of CLT panel are used for calculating the effective bending stiffness,
- shear deformations are considered through connection efficiency factors γ,
- the effect of transverse layers is considered only through their rolling shear properties.

Due to the presence of reinforcement only in tension zone, there is a shift of the neutral axis as presented in Fig. 4.

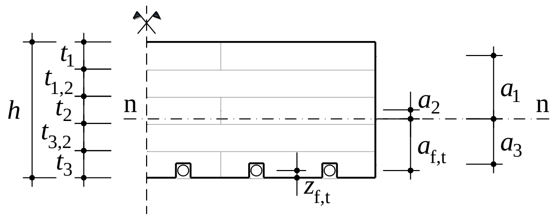

Figure 4: CLT cross-section with shifting of neutral axis due to reinforcement in tension zone

The effective bending stiffness in the longitudinal direction for five-ply CLT panel is defined as follows:

$$\left(EI\right)_{\mathrm{eff}} = E_{\mathrm{w}} \cdot I_{\mathrm{comp,eff}} = E_{\mathrm{w}} \cdot \left[\sum_{i=1}^{n} \left(\frac{b \cdot t_i^3}{12} + \gamma_i \cdot b \cdot t_i \cdot a_i^2 \right) + \gamma_3 \cdot \frac{E_{\mathrm{f}}}{E_{\mathrm{w}}} \cdot A_{\mathrm{f,t}} \cdot a_{\mathrm{f,t}}^2 \right] \tag{8}$$

with

$$\begin{cases} a_1 = \left(\frac{h}{2} - \frac{t_1}{2} \right) + a_2 \\ a_3 = \left(\frac{h}{2} - \frac{t_3}{2} \right) - a_2 \\ a_{\mathrm{f,t}} = \left(\frac{h}{2} - z_{\mathrm{f,t}} \right) - a_2 \\ a_2 = \dfrac{-\gamma_1 \cdot \left[b \cdot t_1 \cdot \left(\frac{h}{2} - \frac{t_1}{2} \right) \right] + \gamma_3 \cdot \left[b \cdot t_3 \cdot \left(\frac{h}{2} - \frac{t_3}{2} \right) + \frac{E_{\mathrm{f}}}{E_{\mathrm{w}}} \cdot A_{\mathrm{f,t}} \cdot \left(\frac{h}{2} - z_{\mathrm{f,t}} \right) \right]}{\sum_{i=1}^{n} \left(\gamma_i \cdot b \cdot t_i \right) + \gamma_3 \cdot \frac{E_{\mathrm{f}}}{E_{\mathrm{w}}} \cdot A_{\mathrm{f,t}}} \end{cases} \tag{9}$$

and

$$
\begin{cases}
\gamma_1 = \dfrac{1}{1+\dfrac{\pi^2 \cdot E_w \cdot b \cdot t_1}{l^2} \cdot \dfrac{t_{1,2}}{G_R \cdot b}} \\
\gamma_2 = 1.0 \\
\gamma_3 = \dfrac{1}{1+\dfrac{\pi^2 \cdot \left(E_w \cdot b \cdot t_3 + E_f \cdot A_{f,t}\right)}{l^2} \cdot \dfrac{t_{3,2}}{G_R \cdot b}}
\end{cases}
\tag{10}
$$

where

n is the number of longitudinal layers,

a_i is distance between the centre point of the i-th longitudinal layer and neutral axis of CLT cross-section,

$a_{f,t}$ is distance between the centre point of GFRP bars in tension zone and neutral axis of CLT cross-section,

l is span of CLT panel, and

G_R is shear modulus perpendicular to the grain (rolling shear modulus) of CLT panel.

4. RESULTS AND DISCUSSION

For using the proposed design model to calculate load-carrying capacity and bending stiffness of (un)reinforced CLT panels, it is necessary to specify the values of stresses and strains that define constitutive models of materials. The most challenging aspect is selecting suitable values for stress limits in timber. The tensile stress limit in bending is greater than the tensile stress limit in axial tension. This fact is taken into account by adopting that CLT panels loaded in out-of-plane bending experience failure in tension zone that occurs upon reaching the bending strength of timber ($f_t = f_m$).

In Tab. 1 are presented mechanical properties of materials that are used in the design model. Presented mean values were derived from characteristic values shown in [7] and coefficient of variations from probabilistic model code [8] that were adopted for glued laminated timber in the absence of data for cross laminated timber.

Table 1: Mechanical properties of materials

	Property	Value
f_m	Bending strength of CLT	33.9 MPa
f_c	Compressive strength of CLT	31.6 MPa
E_w	Modulus of elasticity of CLT	11550 MPa
G_R	Rolling shear modulus of CLT	65 MPa
E_f	Modulus of elasticity of GFRP	50000 MPa
$\varepsilon_{w,t,u}$	Ultimate tensile strain of CLT	2.9‰
$\varepsilon_{w,c,y}$	Yield strain in compression of CLT	2.7‰

Table 2: Comparison of experimental and theoretical results

	Series	Experimental testing	Design model	Difference [%]
Load-carrying capacity [kN]	A	60.8	60.9	0.03
	B	67.2	65.8	-2.05
	C	77.6	70.4	-10.21
Bending stiffness [$\times 10^8$ kNmm^2]	A	11.441	11.839	3.37
	B	12.283	12.469	1.49
	C	12.894	13.055	1.23

Tab. 2 shows the comparison of experimental and theoretical results for all three Series of CLT panels. The displayed values are mean values of load-carrying capacity and bending stiffness from experimental testing with corresponding values calculated using Eqs. 7 and 8 of presented design model.

There is almost no difference between the experiment and design model for unreinforced panels (Series A) in terms of load-carrying capacity. For reinforced panels, somewhat greater difference in load-carrying capacity can be explained by the fact that bending strength f_m of CLT panels increases due to the presence of GFRP bars in tension zone. Reinforcement prevents the opening of cracks, limits local damages, and overcomes wood defects, which allows timber elements to perform better and withstand higher loads. In order to take this reinforcement effect into account, design model needs to be modified and calibrated with the analysis of experimentally measured strains in tension along the height of reinforced CLT cross-section.

Regarding bending stiffness, very good agreement was observed between experimental results and calculated values using the Gamma method with adopted ideal connection between GFRP and CLT. The mean values of bending stiffness determined from experimental testing are lower than theoretical values. These results are expected given the fact that, within the simplified theoretical model, wood is practically considered as a homogeneous isotropic material. The difference in results is lower for reinforced panels as the presence of GFRP reinforcement reduces the variability of characteristics.

5. CONCLUSIONS

It can be concluded that the design model provides a satisfactory prediction that aligns well with the experimental results. This means that the model can be applied in real design situations. However, additional testing of CLT panels with different reinforcement arrangement and percentage is required for the proper calibration of the design model. These tests should complete the calculation process by adopting partial safety factors, so that a safe, reliable, and accurate model can be applied in everyday engineering practice.

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