SOLUTIONS FOR IMPROVING THE SUSTAINABILITY OF REINFORCED CONCRETE ELEMENTS

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Abstract: Improving sustainability of reinforced concrete structures suppose structural measures, technological measures and construction process engineering measures. In this context, the article presents solutions for improving the sustainability of reinforced concrete structures such as: use of precast prestressed concrete elements (purlins); replacing CEM I cement with CEM II/A; using recycled aggregates and self-compacting concrete; replacing in concrete elements of the stirrups in the central area with fiber reinforced concrete. Experimental data obtained for three testing elements (with and without of stirrups) are: longitudinal strains, beam deflection for different level of load. The results presented indicate, in terms of strains, deflection, and cracking, similar behavior of the three tested purlins under test conditions, up to the load values corresponding to normal service loads (no cracks were observed up to this load level) and design loads, respectively.

Key words: prestressed concrete, steel fiber.

1. Introduction

Sustainability is a general concept of a durability and future development policy – based on three dimensions: ecological, economic, and socio-cultural – and represents the starting point to the preparation of developing principles and evaluation criteria for a sustainable construction (Fig. 1). Ensuring the durability of reinforced concrete structures is no longer just a concern strictly related to maintaining the characteristics of exposed concrete in different environments but has gained global importance in relation to the sustainability of the built environment.

Among the key objectives related to improving sustainability in accordance with [3], the following can be highlighted: an immediate and drastic reduction in CO_2 emissions as a measure for climate protection, resource conservation, and material optimization.

In this context, the article presents, through a specific example, multiple and cumulative ways to improve the sustainability of reinforced concrete elements by:

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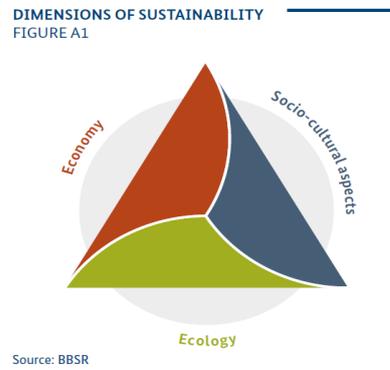
Fig. 1. *The three dimensions of sustainability*

- the use of precast and manufacture of roof elements (purlin) with prestressed concrete;
- the manufacture of the purlins by replacing the transverse reinforcement (stirrups) in the central area with fiber-reinforced concrete;
- technological measures on building materials (use of CO_2-efficient or climate-neutral materials such as cements with additions);
- use of recycled aggregates in concrete production;
- use of self-compacting concrete.

2. Detailing the solutions for improving sustainability applied to precast prestressed concrete elements

2.1. Use of precast concrete, manufacturing roof elements (purlins) with prestressed concrete

The precast solution and in particular the use of prestressed concrete for the realization of structural elements is a good solution to reduce the environmental impact of buildings. In [2], this aspect is highlighted, presenting a case study on different solutions for the realization of a slab (Figure 2). Use of post tension purlins was able to allow an important reduction of concrete and steel mass.

- 391 kg of concrete/m²
- 12,2 kg of steel/m²
- 52,8 kg CO2/m² for the post tensioned concrete slab

→ represents a reduction of the carbon footprint of 60% compared to a reinforced slab

Case study

Fig. 2. *Post tensioned concrete slabs in a commercial building in Madrid.*

The comparison to the quantities used for other solutions such as reinforced concrete and post-tensioned concrete, but non precast are shown in Table 1.

Different structural solutions for buildings with different footprints   Table 1

	Reinforced concrete slab	Post-tensioned concrete slab	Precast (pre-stressed) hollow concrete slab
Concrete weight	700 kg/m^2	515 kg/m^2	475 kg/m2
Steel weight	25 kg/m^2	15 kg/m^2	15 kg/m^2
CO$_2$ footprint	135-150 kg CO$_2$/m^2	110-120 kg CO$_2$/m^2	90-100 kg CO$_2$/m^2
Reduction	---	20 %	33 %

In this context, two solutions of shear reinforcement were used in the central area of the precast prestressed concrete elements with post-tensioned reinforcement (Figure 3). One of the solutions was chosen also for improving the sustainability of the construction.
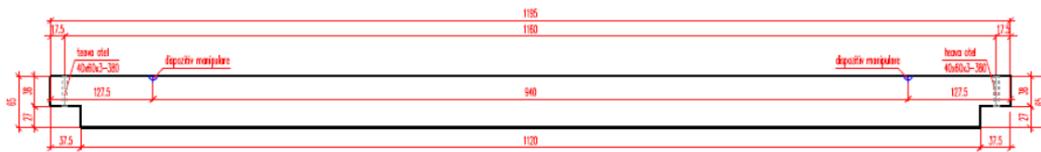

Fig. 3. *Beam features: span=11.5m, beam depth=65 cm*

2.2. The use of metal fibers as an alternative solution to steel reinforcement, a solution to reduce the consumption of steel for concrete

This measure will lead to a reduction in steel concrete consumption but obviously this solution needs experimental validation. The experimental test results are presented in section 3.

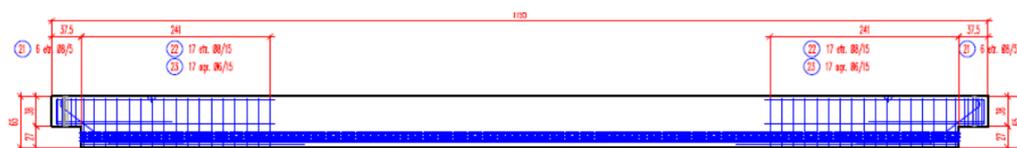Fig. 4. *Precast prestressed concrete with transverse reinforcement*

Fig. 5. *Precast prestressed concrete (fiber reinforced with no transverse reinfocement in middle area)*

The experimental tests monitored the behavior of three prestressed reinforced concrete purlins, with concrete class C50/60, one purlin with transverse reinforcement (stirrups) in the central area marked Gff (Figure 4) and two with fiber reinforcement marked G1f and G2f. (Figure 5). The solution of using fiber concrete was meant to improve sustainability.

Concerning fiber reinforced concrete, the properties of this type of concrete are influenced by the presence of fibers both in the fresh state, i.e. fluidity, viscosity and workability in the case of self-compacting concrete, and in the hardened state, particularly in terms of tensile strength. For this reason, the classification of fiber reinforced concrete in terms of strength and ductility is carried out by specific test methods, which are different from the determinations usually made for the classification of ordinary concrete.

The specific behavior of fiber reinforced reinforced concrete at different types of stresses compared to ordinary concrete is reflected in particular design rules which mainly consider the contribution of fibers in the tension areas of the elements.

The advantages of using fiber-reinforced concrete are highlighted by the increases in load-bearing capacity recorded in bending with shear force and in terms of reduced crack opening.

In terms of the shear strength of fiber-reinforced concrete, the fibers increase the strength of both non-transverse-reinforced and transverse-reinforced elements.

For members without transverse reinforcement, the presence of fibers improves the cracking behavior by delaying the onset of a crack developing over the entire height of the member and leading to failure of the member. By crossing the crack, the fibers limit the crack opening, improve the interlock effect in the crack propagation zone and thus have the effect of increasing the shear strength.

The design at shear can be done according to Annex L of SR EN 1992-1-1:2024 [6].

For steel fiber reinforced concrete with longitudinal reinforcement bars in the tension area, the shear strength is determined as:

$$\tau_{\mathrm{Rd,cF}} = \eta_{\mathrm{cF}} \cdot \tau_{\mathrm{Rd,c}} + \eta_{\mathrm{F}} \cdot f_{\mathrm{Ftud}} \geq \eta_{\mathrm{cF}} \cdot \tau_{\mathrm{Rdc,min}} + \eta_{\mathrm{F}} \cdot f_{\mathrm{Ftud}} \tag{1}$$

where

$$\eta_{\mathrm{cF}} = \max\{1{,}2 - 0{,}5 f_{\mathrm{Ftuk}}; 0{,}4\} \leq 1{,}0$$

$$\eta_F = 1{,}0; \tag{2}$$

The minimum shear strength of concrete without transverse reinforcement, $\tau_{Rdc,min}$, is determined following:

$$\tau_{\mathrm{Rdc,min}} = \frac{11}{\gamma_{\mathrm{V}}} \cdot \sqrt{\frac{f_{\mathrm{ck}}}{f_{\mathrm{yd}}} \cdot \frac{d_{\mathrm{dg}}}{d}} \tag{3}$$

where:

γ_V partial safety coefficient for shear design equal to 1,40;

f_{yd} yield design strength used to design the bending reinforcement;

d is the effective depth of the beam;

d_{dg} is a size parameter describing the roughness of the failure zone, which depends on the type of concrete and its aggregate properties. It is allowed that d_{dg} (mm) is taken as:

- $16\,mm\,+\,D_{lower}\,\leq\,40\,mm$ for concrete with $f_{ck}\,\leq\,60$ MPa;
- $16\,mm\,+\,D_{lower}(60\,/\,f_{ck})^2\,\leq\,40\,mm$ for concrete with $f_{ck}\,>\,60$MPa.
- D_{lower} is the smallest value of the upper sieve mesh size at the top level D of an aggregate for the coarsest aggregate fraction of concrete allowed by the concrete specification. If D_{max} is known, D_{lower} may be replaced by D_{max}.

2.3. Technological measures relating to building materials (use of CO2-efficient or climate-neutral materials such as cements with additions

In this study, the possibility of using cement with additions is studied, since until now, the only possibility for using in prestressed concrete in Romanian norms was a CEM I cement [5]. Thus, CEM II/A cement was chosen. The use of cements with additions is perhaps the best known and also the most effective measure to reduce the environmental impact of reinforced concrete elements. Table 2 [2] shows the environmental impact of different types of cements in conjunction with concrete performance. CEM II/A type cement falls into the category of medium impact (line 5 of Table 2).

Environmental impact related to concrete strength for several cements   Table 2

1	Designation	C20/25	C25/30	C30/37	C35/45	C45/55	C50/60
2		Performance-related greenhouse gas emissions[1] in kg CO_2-Equivalent/(m³ x MPa)						
3	Concrete for example with CEM VI or similar	4,3	4,1	3,7	3,5	3,4	3,3
4	Concrete for example with CEM III/A, CEM II/C or similar	4,9	4,6	4,3	4,0	3,9	3,8
5	Concrete, current average	6,1	5,8	5,3	5,0	4,8	4,7
6	Concrete with CEM I	7,3	7,0	6,4	5,8	5,3	5,1
[1] Calculation of the values based on average compressive strength f_{cm}, cube: Example C20/25, line 3: 125/(f_{ck} + 4) = 125/29 = 4.3.							

This consideration is generated by the fact that the CO_2 emissions may not be the only parameter that should be considered when classifying cement. It deals rather with the conversion ratio between emissions and strength than to the quantity of emissions. Figure 6 show that cements with weaker emissions can be less efficient in ensuring strength than

others with more emissions, but stronger. So, the performance-related to the greenhouse gas admissions must be considered.
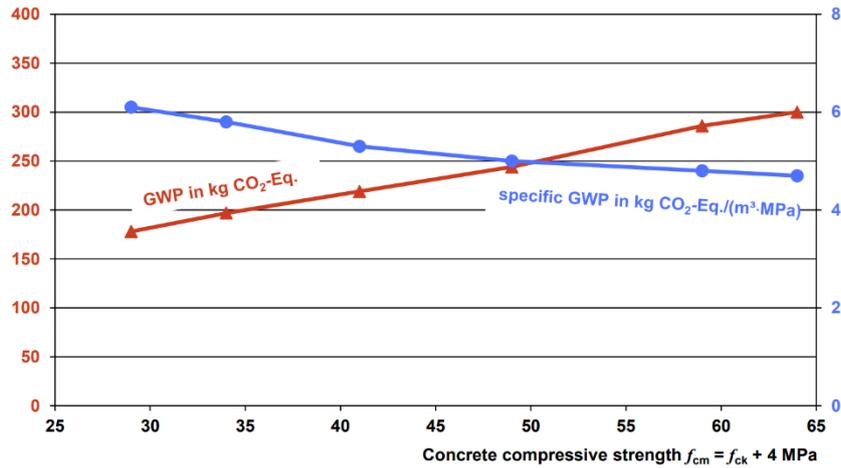

Fig. 6. *Relationship between concrete compressive stregth and global warming potential (GWP) or performance-related global warming potential (specific GWP).*

One example to illustrate the need for cement to ensure performance is illustrated in Fig. 7. In this figure, it is shown that reducing water / cement ratio can increase carbonation resistance class (RXC) and the compression strength for a concrete with this cement, CEM II/A. Performance to carbonation is an aspect that is environmentally positive and the entire concept illustrate that by increasing cement content (and thus decreasing w/c), environmental behaviour can improve in certain aspects.
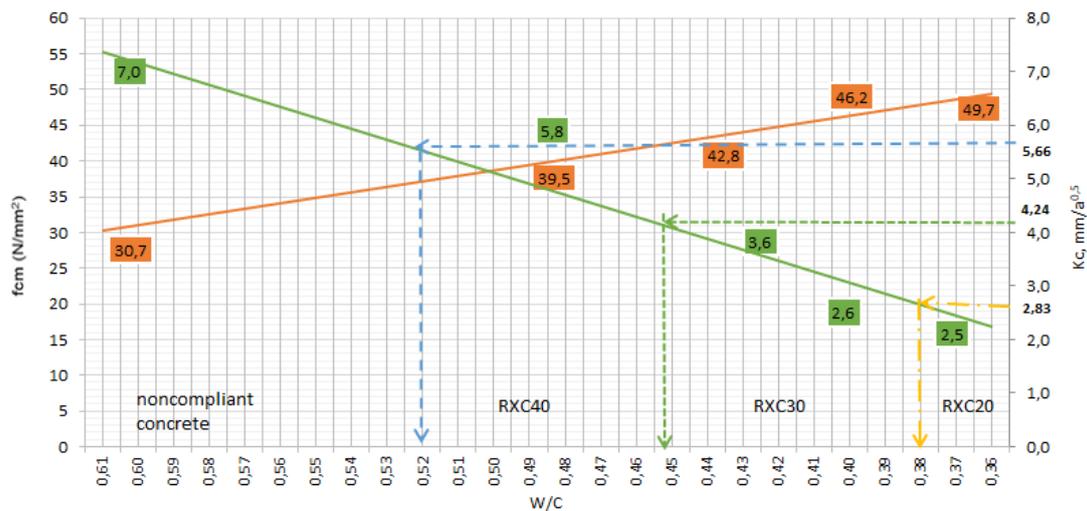

Fig. 7. *Exposure resistance classes* [4].

In addition to the durability aspects, the use of cements with additions in prestressed concrete elements must also take into account other concrete characteristics, such as long deformations, shrinkage and creep of the concrete (especially because in this case self-compacting concrete was used), which can be determined experimentally (Figure 8).

Fig. 8. *Experimental tests performed to determine concrete properties*

Creep, elasticity and shrinkage tests indicate similar properties to the concrete manufactured with CEM I, thus indicating the possibility to use CEM IIA

2.4. Using recycled aggregates in concrete production

The use of recycled aggregates is another useful measure to reduce the environmental impact of construction. Their use is generally limited according to exposure classes (Table 3).

Coarse recycled aggregates with a quantitative ratio $\alpha_{RA} = 0.2$ of the mass were used. For prestressed concrete, following [6], when $0 < \alpha_{RA} \leq 0,20$ the values of properties in Table 4 should be used or values should be determined by testing.

Table 3

Maximum percentage of replacement of coarse aggregates (% by mass) [1]

Recycled aggregate type	Exposure classes			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes [a]
Type A: (Rc_{90}, Rcu_{95}, $Rb_{10\text{-}}$, $Ra_{1\text{-}}$, $FL_{2\text{-}}$, $XRg_{1\text{-}}$)	50 %	30 %	30 %	0 %
Type B [b]: (Rc_{50}, Rcu_{70}, $Rb_{30\text{-}}$, $Ra_{5\text{-}}$, $FL_{2\text{-}}$, $XRg_{2\text{-}}$)	50 %	20 %	0 %	0 %

[a]   Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30 %.
[b]   Type B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.

Table 4

Changes in concrete properties due to the use of recycled aggregates

Property	Rules and provisions	Diffference with respect to normal concrete
Compression strength	$f_{ck} \leq 50 MPa$	No difference
Elasticity Modulus	$E_{cm}(normal\ concrete) \cdot (1 - 0.25 \cdot \alpha_{RA})$	-4.5%
Stress/Strain relationship	$\varepsilon_c \cdot (1 + 0.33 \cdot \alpha_{RA})$	+6.7%

2.5. Using self-compacting concrete;

The attribute of self-compaction of concrete was achieved by using admixtures and adjusting component ratios.
The main advantages of using self-compacting concrete are:
- Concerning manufacture:
  - Reducing noise;
  - Reducing issues related to vibration;
  - Reducing workmanship;
  - Improving speed of execution.
- Concerning final properties of concrete:
  - Improving durability by improving quality of the cover layer.

Even if self-compacting concrete present specific component ratios with respect to normal vibrated concrete, tests show that hardened concrete properties are suitable also for self-compacting concrete.

3. Experimental research carried out on purlin-type elements

Bending tests were performed on the three purlins. The experimental tests monitored the behavior of three prestressed reinforced concrete purlins, concrete class C 50/60, one purlin with transverse reinforcement (stirrups) in the central area marked Gff and two with fiber reinforcement marked G1f and G2f (Figures 4 and 5). While bending tests were performed, devices for the measurement of longitudinal strains and vertical deflections were placed in the main interest section. In Fig. 9, the loading system and the measuring systems for tested purlin is presented.

Fig. 9. *Loading and measurement layout system.*

The values recorded and analyzed based on the data measured during the test were as follows:

(i) - strains of concrete in the compression and tension areas, determined based on strains at the measurement level;

(ii) - beam deflection at the middle of the span (f), represented as a function of load;

(iii) - values at which purlin failure occurred and the type of failure.

The results presented indicate, in terms of strains, deflection, and cracking, similar behavior of the three tested purlins under test conditions, up to the load values corresponding to normal operating loads (no cracks were observed up to this load level) and design loads, respectively (Fig. 10).

The maximum load was similar for purlins G1f, G2f and Gff. The failure mode was different for fiber-reinforced purlins, specific to prestressed reinforced concrete elements, but particular to Gff, given the type of reinforcement in the central area (Fig. 11). Gff beam presented typical bending failure, while the fiber reinforced ones presented typical shear failure at the critical section at the end of the loading profile, where no-transverse reinforcement zone begins also.
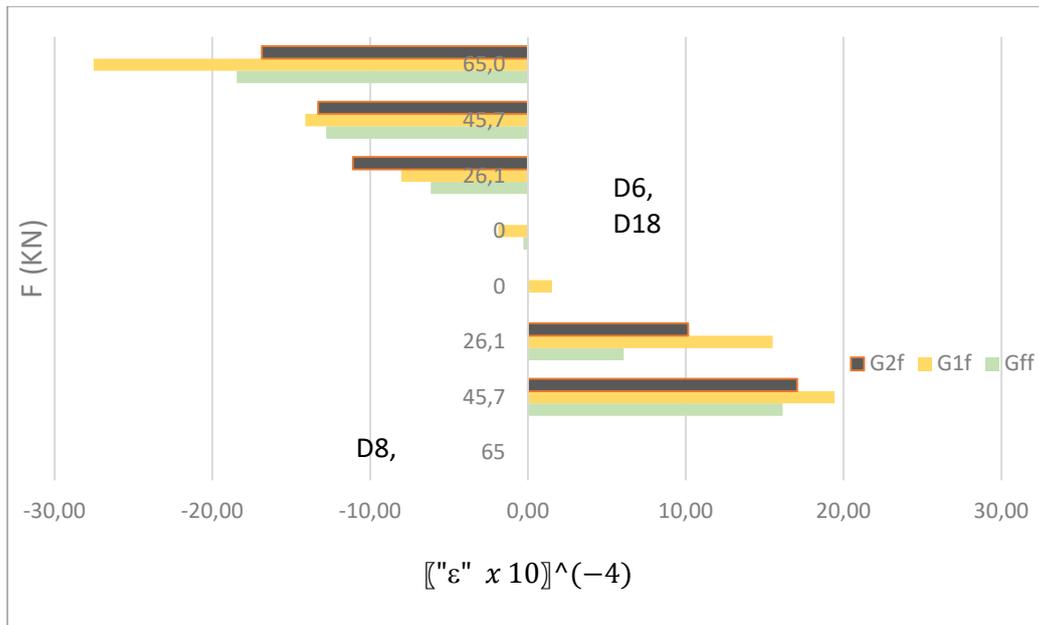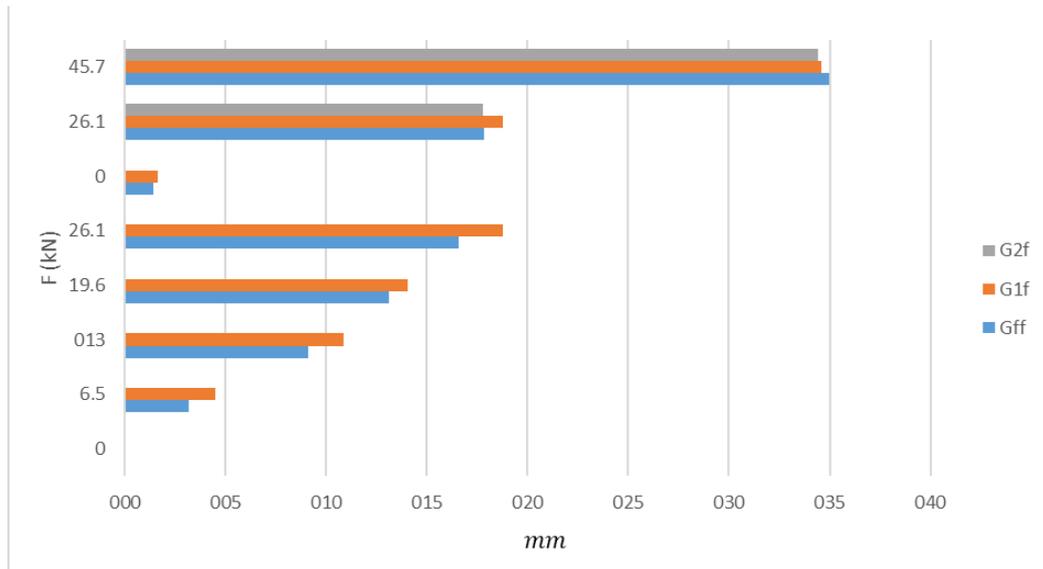
Fig. 10. *Recorded strain and deflection values.*

Fig. 11. *Failure mode for conventionally transverse reinforced (left) and fiber reinforced beam (right).*

Conclusions

1. The present article has highlighted multiple interrelated methods to improve the sustainability of reinforced concrete elements:

At the structural level:

- The possibility to address new concepts regarding the design of fiber-reinforced and recycled aggregate-reinforced concrete and to ensure the durability of the elements;

At material level:

- The use of cements with CEM II /A type additions with lower environmental impact for prestressed concrete elements;
- Use of a C50/60 grade concrete with a good performance/environmental impact ratio;

- Use of recycled aggregates;
- The use of fiber reinforced concrete to reduce the consumption of steel in concrete;

At the concrete production level:
- The use of self-compacting concrete

At the level of construction technologies:
- Production and use of precast elements;

2. Reducing the environmental impact and improving the sustainability of concrete elements/structures cannot be analyzed without also referring to performance:
- optimization of sections by choosing types of elements that lead to a reduction in material consumption, ensuring better material utilization, better stiffness and a better ratio between weight and stiffness;
- the use of materials with superior characteristics, ensuring an increase in strength for the same weight and therefore an improved performance/environmental impact ratio.

3. Considerations on the experimental results obtained on the tested purlins:
- The presented results indicate, in terms of strains, deflection and cracking, a similar behavior of the three tested purlins, under the test conditions, up to the load values corresponding to the normal service loads (no cracks were observed up to this load level) and design loads, respectively;
- The failure load was similar for G1f and G2f compared to Gff. The failure mode was different in the case of fiber-reinforced purlins, specific to the failure of the elements at shear forces in inclined sections and therefore particular considering the reinforcement mode in the central area;
- It is recommended that in the case of eliminating the transverse reinforcement the stirrups should have spacings higher than the previous ones (with the observation that there should be no sudden variations of the transverse reinforcement area along the beam) in order to avoid the shear force failure.

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