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Analyzing the minimum degree of shear connection for composite beams with prestressed dismountable shear connections

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ABSTRACT: The construction sector is responsible for 37% of global energy and process emissions, with materials like concrete, steel, aluminum, bricks, and glass contributing 9% of CO2 emissions. To reduce emissions, the industry must adopt a circular economic approach, focusing on material and structure lifecycles. Composite structures, such as those proposed by the RFCS project "REDUCE" (2016), offer solutions through demountable designs using bolts as shear connectors. Bolted connections exhibit a tri-linear load-slip behavior, differing from welded shear studs. An analytical algorithm and a numerical study using ABAQUS© software were developed to understand this behavior. The study aims to characterize slip behavior in shear connections, particularly for beams with a low degree of shear connection and compare it to the maximum allowable slip of 6mm from EN1994-1-1. The goal is to assess the applicability of the proposed algorithm and EN1994-1-1 standards for new bolted shear connections.

1 INTRODUCTION

Due to the increasing demand and necessity for reduced CO2 emissions, with the goal to reach net zero or carbon neutrality by 2050, it appears as obvious that one of the biggest contributors to global CO2 emissions, namely the building and construction sector with approximately 37% of global energy and process emissions (UN environment programme), must rethink the process of producing and handling economic goods. According to the 2022 global status report for buildings and construction made by the UN global alliance for buildings and construction (GABC), 9% of the CO2 emissions were emitted in the manufacturing process of concrete, steel, aluminum, bricks and glass. The use of composite beams to reduce costly materials (e.g., steel) and add a cheaper material, like concrete, to achieve a better structural behavior, allowed for more economically efficient solutions in the construction field. However, one problem arose: the classical steel concrete composite design does not enable easy recycling and follows a linear economy (built to be disposed at the end of the lifecycle), which is not in line with the recommendation for circular economy, identified as the best approach to reach carbon neutrality by 2050. The idea is to recycle or even reuse the old materials to limit or even avoid emissions.

To understand how to achieve circular economy in composite beams, the research project "REDUCE" (grant No. 710040, 2016) was launched within RFCS (Research Fund for Coal and

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Steel) program. REDUCE focused on demountable systems of shear connections in steel-concrete composite beams. The idea was to allow for easy disassembly of components using demountable shear connections mainly based on bolted connections. Through this research, a viable option to replace and reuse components and enable modular connections was confirmed.

In particular, to analyze and estimate the structural behavior of the demountable shear connections as well as the overall performance of the composite beam, tests were conducted and an analytical algorithm was proposed and validated to characterize the effective shear connection capacity equivalent to "P_{Rd}" as defined in EN 1994-1-1 (see Section 4). Accordingly, this effective shear connection capacity is used as a translation to the calculated design resistance of EN 1994-1-1: 6.6.3.1, Formula 6.18, respectively 6.19.

Within the present paper, the obtained results are summarized and reviewed.

2 OVERVIEW OF SHEAR CONNECTIONS: BOLTED AND EUROCODE 4 SHEAR CONNECTORS

2.1 *EN 1994-1-1 (2004)*

The current Eurocode 4 mainly deals with two types of shear connectors, which can be characterized through experimental tests as defined in see EN 1994-1-1: Annex B. One type is defined as a non-ductile or rigid connector (see Figure 1b) and the other is defined as a ductile shear connector whose behavior is idealized as a bilinear curve (see Figure 1a), considering that the full shear force capacity is reached at 1mm slip and that the maximally allowable slip is 6mm (EN 1994-1-1: 6.6.1.1 (5)). Looking to the design rules as presently proposed in EN 1994-1-1, the latter only cover the design of welded shear stud connectors. Other connector solutions and, specially, demountable bolted shear connectors, are not addressed.

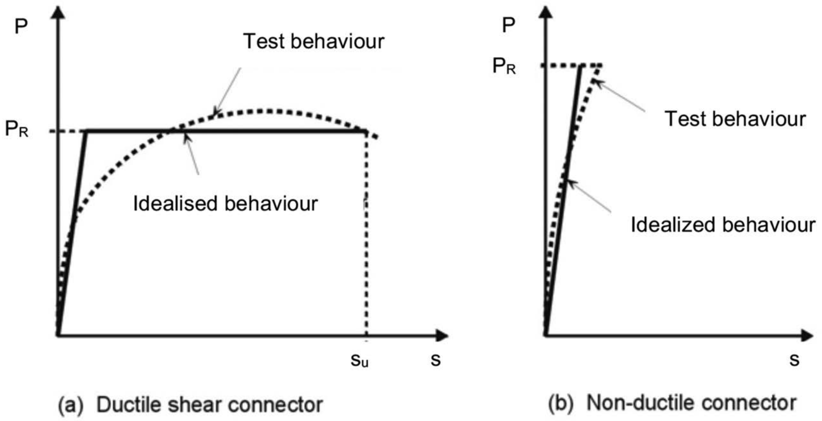


Figure 1. Ductile and non-ductile shear connectors (EN 1994-1-1).

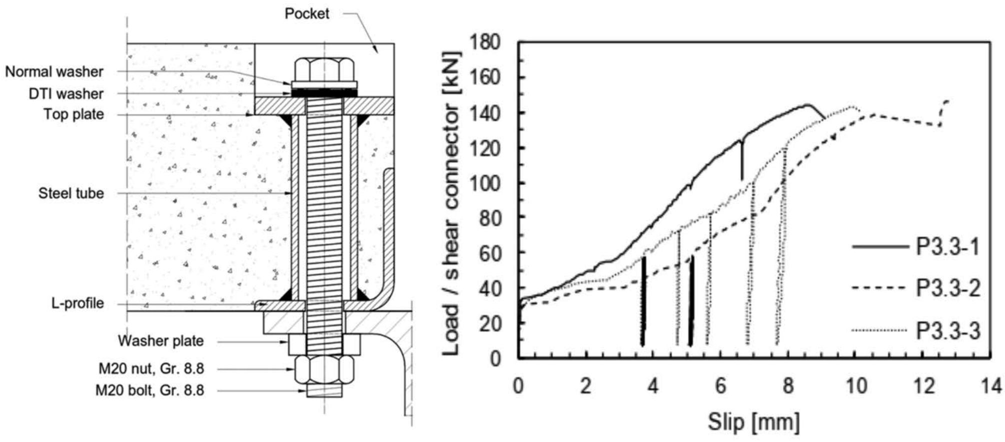
2.2 *prEN 1994-1-1*

Recognizing the gap of information, extensive investigations on various shear connectors have been initiated. Consequently, the upcoming revision of Eurocode 4 will incorporate a total of four distinct types of shear connectors, each exhibiting different behaviors.

a) Ductility Category D1 (brittle behaviour), b) Ductility Category D1 (flexible behaviour with multilinear curve), c) Ductility Category D2 and D3 (ductile behavior), d) Ductility Category D2 and D3 where the design longitudinal shear stress is to be modified by a ratio α according to Clause (5). [prEN1994-1-1].

2.3 *Other shear connections*

Examining other types of connections as to enable circular economy, it was recognized that the load-slip behavior was different to the ones described in section 2.1 and 2.2. Kozma developed shear connections based on demountable bolts (P3 and P15, see Figure 2a) for P3.3 example connection). Bolted connections show a more tri-linear load-slip behavior (see Figure 2b)) were there is a "load-plateau" with increase of slip. During this phase the bolt shifts in its hole.



(a) (b)

Figure 2. a) P3.3 connector system, b) P3.3 shear connector experimental load-slip curves [Kozma].

3 ALGORITHM TO DETERMINE AN EFFECTIVE SHEAR CONNECTION RESISTANCE

3.1 *Kozma algorithm*

To be able to analyze the degree of shear connection for any shear connectors Kozma suggested an algorithm which delivers an effective shear connection resistance $P_{Rd,effective}$. This requires: (i) the load-slip curve of the shear connection, (ii) a function for the progression of the slip along the shear connection in the longitudinal direction of the beam and (iii) a limit value for the maximum permissible final slip in the composite connection (i.e. 6mm from EN1994-1-1).

For the function of the progression of the slip along the beam, a linear curve would be a conservative assumption. However, for steel-concrete composite beams, the cosine curve in the ultimate limit state has proven to be rather realistic and conservative [Kozma].

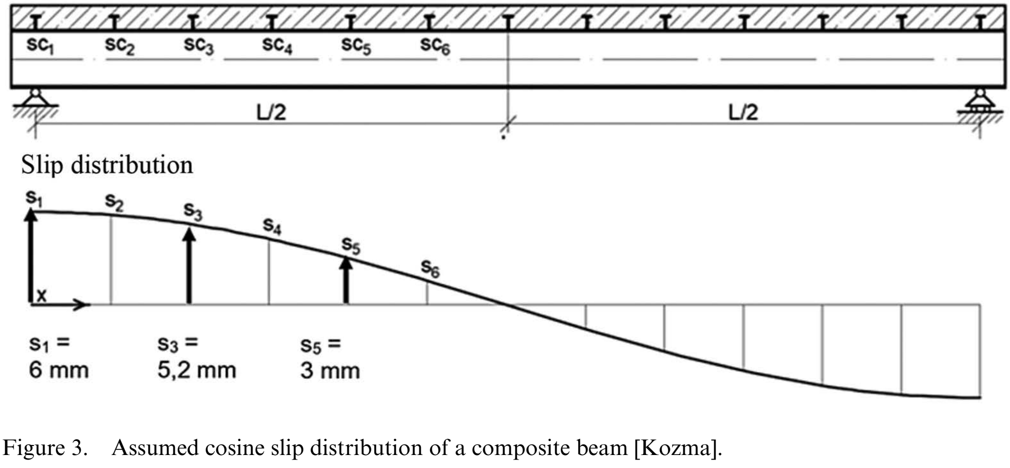


Figure 3. Assumed cosine slip distribution of a composite beam [Kozma].

Accordingly, under these assumptions, the slip distribution along the beam follows a cosine distribution (see Figure 3). The slip at each position can be assumed with the following formula:

$$s(x) = s_1 \cdot \cos\left(\frac{\pi \cdot x}{L}\right) \tag{1}$$

Where: s(x) = slip at position x; s_1 = slip at the end of the beam; x = position along the beam; L = length of the beam.

Using the calculated slips and the known load-slip curve of the shear connection, it is possible to assess the contribution of each shear connector (or shear connector pair) and assign a force to it, see Figure 4.

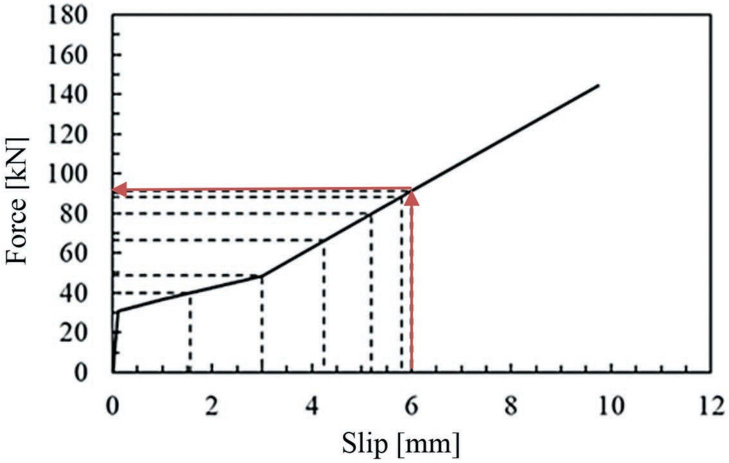


Figure 4. Example of assigning a force to a slip using an idealized load-slip curve of a connector.

After assigning all shear connectors with a corresponding force, an effective force can be derived as the average force of all shear connectors (see example in Table 1).

Table 1. Example of assigning a force to a slip using the given load-slip curve.

Position [x/L]	Shear Connector	Slip [mm]	Force P_i [kN]
0,00	SC_1	6,00	1,000 P1
0,08	SC_2	5,80	0,966 P1
0,17	SC_3	5,20	0,866 P1
0,25	SC_4	4,24	0,707 P1
0,33	SC_5	3,00	0,500 P1
0,42	SC_6	1,55	0,259 P1
			Sum = 4,298 P1
			P_{eff} = 4,298 P1 /6 = 0,716 P1

By utilizing the force at the maximal allowable slip (for example 6 mm) and dividing the resulting average force by this value, a scaling factor, termed k_{flex} by Kozma, is obtained. Numerical analysis of his shear connectors with different number of rows showed, that using 4 to 30 rows give the k_{flex} values between 0,69 and 0,81. Upon analyzing this factor, Kozma concluded that the use of a minimum of six shear connectors on half the span of the beam (or 12 on the full length) leads to an almost constant value of k_{flex}, see Figure 5. The difference in the effective average shear connector force when using six or more connectors being negligible.

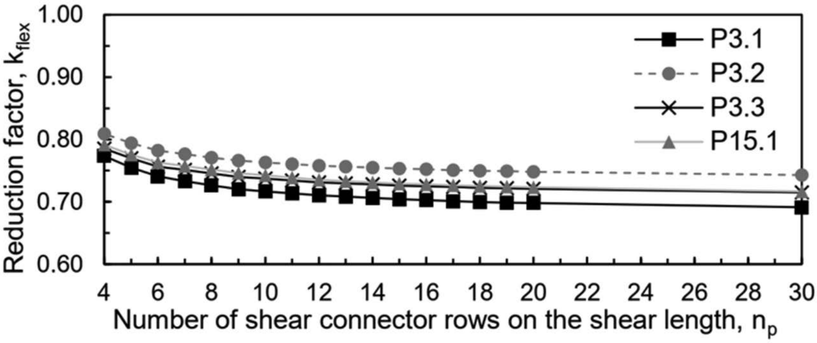


Figure 5. Behavior of k_{flex} according to the use of number of shear connectors [Kozma].

4 CASE STUDY: KOZMA-ALGORITHM ON STEEL CONCRETE COMPOSITE BEAMS WITH LOW DEGREE OF SHEAR CONNECTION

4.1 *Flowchart*

For a specific set of date (composite cross-section, used materials and the load-slip curve of the shear connection) the Kozma algorithm is employed to derive an effective shear connection capacity “P_{eff}” (see chapter 3). It is then used in alignment to EN1994-1-1 Annex B2.5 to derive a “$P_{Rd,eff}$”, considering a security factor γ_{M2}=1,25 and a reduction factor of 0,9 (10% reduction of the characteristic resistance). This enables the calculation of the moment bending capacity of the composite beam with partial shear connection according to EN1994-1-1.

Translating this bending moment capacity into a uniformly distributed load and applying it on a numerically simulated beam (e.g. using Abaqus©) gives us a simulated maximal slip under the load as well as a deflection. Ultimately, the maximal allowable slip as specified in EN 1994-1-1 can be compared to the numerically derived slip to investigate if the recommendation as specified in EN 1994-1-1 are sufficient to ensure an appropriate behavior of a uniformly loaded composite beam. Figure 6 shows the flowchart of this procedure.

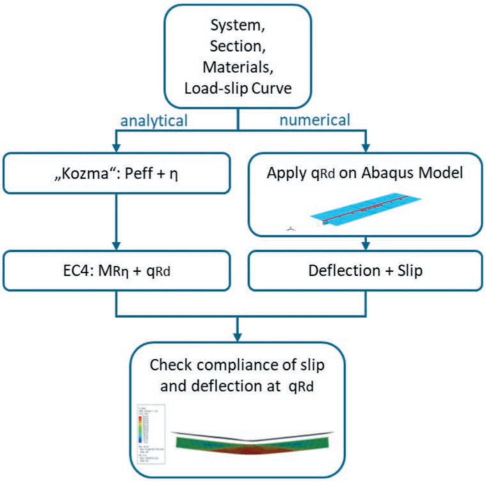


Figure 6. Flowchart of analysis using Kozma algorithm.

4.2 *Overview of the parametric study*

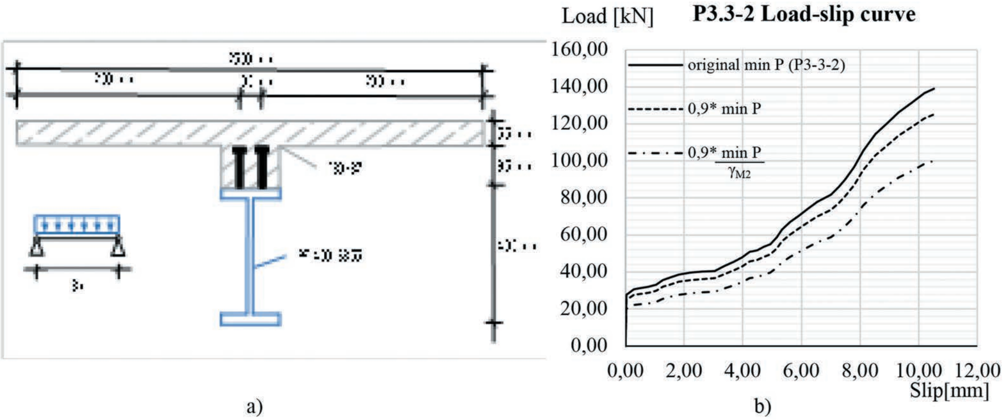
A total of fifteen composite beams were analyzed. Their designation is as follows:

8E36, 12E36, 16E36, 8E40, 12E40, 16E40, 8E45, 12E45, 16E45, 8B36, 12B36, 16B36, 8BS36, 12BS36, 16BS36;

where the number at the beginning reflects the length of the system (i.e. 8m, 12m and 16m), the better "E" implied an IPE profile and the letter "B" implies and HEB Profile. The number "36" implies the profile type as 360, "40" implies 400 and "45" implies 450. The addition "S" in the last 3 systems indicate that, instead of a S355 steel, a S460 steel was used. All system used a 2,5m wide composite slab with C30/37 concrete with a ComFlor® 80 transversal metal sheeting (95mm sheeting height). The P3.3 shear connector developed by Kozma is used (see Figure 7).

4.3 *Example: Composite Beam 8E40*

The system consists of a simply supported 8m long beam, see Figure 7. It uses an IPE 400 with a steel grade of S355. The Elasticity-Modulus was taken as 210.000 N/mm^2. The total height of the concrete slab is 150mm and the concrete height above the steel sheeting profile is 55mm. The E-Modulus was calculated according to prEN1992-1-1 as 31.939 N/mm^2. The design compressive strength was taken as 17,00 N/mm^2**.**



a) b)

Figure 7. a) Section of the example beam "8E40" and b) P3.3-2 shear connector load-slip curve.

Using the "Kozma Algorithm" on his shear connector P3.3-2 Series [Kozma], the effective shear capacity can be calculated. To compute a design resistance of the shear connection, the original curve is modified using 0,9*P_{min}, where P_{min} are the forces at any slip. Subsequently, reducing it by the safety factor γ_{M2}=1,25 and using the average force of the shear connectors, the shear resistance capacity is determined. In this case, the shear resistance capacity is 36.20 kN. A total of 60 shear connectors are used in pairs along the beam with a starting displacement of 85mm and a spacing of 270mm. This results in a degree of shear connection of η = 0,553. According to prEN1994-1-1, Equation 8.13, the required minimum degree of shear connection is to be calculated as following:

$$\eta \geq \eta_0 \rho_m^2 k_{up} \geq \eta_{min} \tag{2}$$

Where: η = the degree of shear connection; η_0 = the degree of shear connection taking into account the length and geometry (eq. 8.14 to 8.19 of prEN1994-1-1), here η_0 = 1-(355/f_y) (0,75-0,03·L_e); ρ_m = reduction factor according to the beam utilization rate: M_{Ed}/(0,95$M_{Rd\ (\eta)}$) ;but 0,8 ≤ ρ_m ≤ 1,0; k_{up} = factor to account for construction process (propped/unpropped), here propped → k_{up}= 1,0; η_{min} = general minimum degree of shear connection according to the ductility (here 0,4).

Equation 2 results in a minimum degree of shear connection of η = 0,49 which is below the degree of the available shear connection of the beam of η = 0,533. Using the acquired design shear resistance of the shear connection, the maximum bending capacity under partial shear connection can be calculated ($M_{Rd,\eta,Peff}$ = 692,20 kNm) and then translated into a uniformly distributed load (q_{Rd} = 86,53 kN/m = 692,2*8/L^2). Following the flowchart from Figure 6, after calculating the bending capacity and transferring it into a uniformly distributed load, the validity of the analytically obtained results can be confirmed using a precalibrated numerical model.

5 NUMERICAL SYMULATION USING FE-SOFTWARE ABAQUS ©

A numerical model is used to confirm the calculation with regards to the Kozma algorithm. The numerical model will be analyzed using a non-linear method with finite elements. In this model design values of the materials are employed instead of experimental values. Design values are intentionally reduced to account for uncertainties and variability in material behavior, ensuring a conservative and safe design. The use of reduced values aims to demonstrate that the model reflects unfavorable material conditions, assuring adequate real-world scenarios. Hence, if it proves that the end-slip of the simulated beam using reduced values is still in compliance with the maximal allowable slip of 6mm, the beam is appropriately characterized using the Kozma algorithm. The beam was modelled using shell elements. The concrete slab was modelled as an extruded line, where the line represents the top surface of the slab (material law see Figure 8).

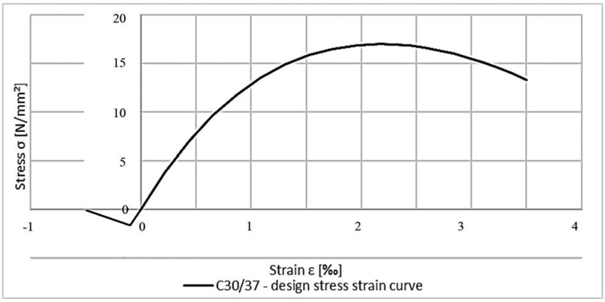


Figure 8. Concrete material law design values.

For the steel profile, instead of modelling it as a beam element, the flange and the web were also modelled as a shell element. Here the lines represent the middle axis. The shear connection was modelled using the fastener engineering feature in Abaqus©. It allows for the use of nonlinear spring laws with the "Slot + Align" function. While the "Slot" function allows for the horizontal movement of the connection the "align" function keeps both ends of the connection (see Figure 9) aligned, which allows the connection to follow the rotation/ deflection of the beam.

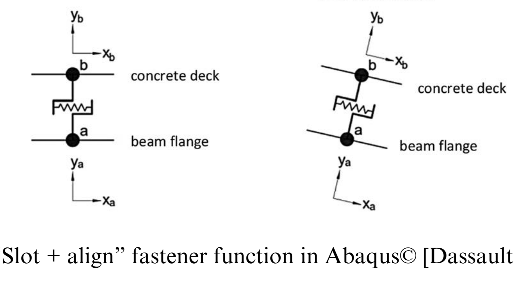
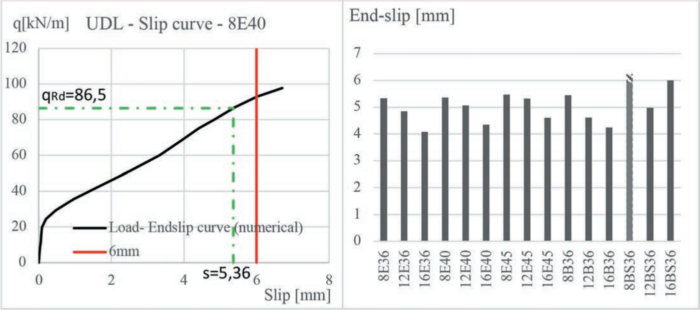


Figure 9. Model of the "Slot + align" fastener function in Abaqus© [Dassault Systèmes].

6 RESULT AND COMPARISON

Figure 10a) shows the result for the example beam “8E40”. The Kozma algorithm in combination with EN1994 leads to a force of q_{Rd} = 86,53 kN/m. The numerical model, using design values to simulate an unfavorable model of the composite beams, leads to a maximum slip of 5,36mm under the load. Utilizing the Kozma algorithm to estimate the bending capacity of a composite beam is viable, even in low degree of shear connection. The end slip under the uniformly distributed load is below the 6mm defined by EN1994-1-1 for all the considered beams in the performed parametric study (see Figure 10b)), except beam 8BS36 (s= 6,24mm). Applying the ß-factor for high steel grades of prEN1994-1-1 brings it again down below 6mm.



a) b)

Figure 10. a) Load-slip curve of composite beam “8E40”, b) End-slip of all analyzed beam types.

7 OUTLOOK

For further research, the behavior under varying degrees of shear connection will be analyzed as well as different beam types, material types as well as different shear connection types. Furthermore, with view on case “8BS36” the influence of the ß-factor of prEN1994-1-1 with high strength steel beams must be investigated in more detail.

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