

# 6

## Application example: Structural optimization

### 6.1 Introduction

Up to now, the main Chapters of this thesis 3, 4 and 5, have pursued one particular idea: to accurately characterize whether analytically, numerically or experimentally, the mechanical behaviour of the VE CLD treatment studied, trying to reliably predict and measure the actual amount of additional damping ratio it may provide. However, the main aim of this thesis, as previously stated in Chapter 1 is: *'To provide the necessary perspective, knowledge and tools for building engineers to study the viability of this solution (the integration of CLD treatments) and if deemed necessary, to accurately and efficiently integrate it into future lightweight floor designs.* This aim can only be achieved by facing the structural optimization of composite floors with and without using CLD treatments and comparing the results obtained to see in which cases the CLD solution can be competitive enough. This Chapter aspires to accomplish that comparison.

When facing the structural design of composite floors prone to vibrate excessively (long-span and slender floors, or lightweight floors), structural designers often try to solve the vibration in two ways: i) Including stiffer-enough steel members (that raise the natural frequencies of the floor to avoid low-frequency resonances), or ii) making use of heavy

concrete slabs that decrease the amplitude of the vibration [179]. This practice leads to a significant increase in the material used on the floor (especially relevant when the vibration limits to comply are very restrictive) affecting its lightness and increasing its EC as has been proved by Gonçalves and Pavic [4]. This research studies the structural oversizing to be performed in a composite floor of  $30\text{ m} \times 44\text{ m}$  with bays of  $6\text{ m} \times 10\text{ m}$  when the VSLS to be met becomes more restrictive (changing from a limiting response factor  $R = 8$  with an rms acceleration of  $0.04\text{ m/s}^2$  to an  $R = 4$  with  $0.02\text{ m/s}^2$ ). They concluded that the floor weight should be increased by 27% and its EC by 14% to accomplish the new comfort level.

Alternatively to this conventional design approach, the integration of damping strategies into the floor's design, as the CLD treatment studied in this thesis, may be an effective way of improving their dynamic performance and minimizing the increase of the structural mass needed for that, thus, reducing as much their EC. This is a key point considering that floors are responsible for around 40% of the total EC of the superstructure of a building [180], [181].

Thus, this Chapter aims to provide a methodology for the structural checking and structural optimization of 'lively' composite floors that integrate the CLD treatment object of study in this thesis. The main objective is to prove that the use of this VE CLD treatment enables overcoming the VSLS without adding great amounts of additional mass to the floor and minimizing its EC. To focus better on the topic covered in this Chapter, a brief state-of-the-art related to the structural optimization of composite floors has been included below.

The structural optimization of composite floors has been researched by many authors using different optimization algorithms, Objective Functions (OFs), and problem constraints (which are the limits states (LSs) to be met by the floor). Initially, the authors used the weight and the cost of the floor as OFs. Zahn [182], optimized the weight of a set of composite beams using two different codes. The VSLS was considered according to an early recommendation given by Murray in 1981 [68] based on a heel drop loading. He concluded that vibrations were the sizing criterion for spans between 3 m and 6 m. Later, Kim and Adeli [183], [184] optimized the economic cost of composite floors with a simple OF considering the influences of concrete, steel, and studs. They affirmed that the VSLS was checked but without providing details. The cost optimization performed by Klanšek and Kravanja [185]–[187] used a complex OF accounting for material, energy consumption, and labor cost items required to manufacture a composite floor. They studied the use of different types of steel members for typical ranges of spans and loads,

according to the Eurocodes but without considering the VSLs. The research developed by Kaveh and Ahangaran [188], [189] followed a similar methodology as the one proposed by Zahn but they focused on testing the efficiency of novel meta-heuristic algorithms for structural optimization. Poitras et al. [190] was the first author to include a widely accepted methodology to check the VSLs (the AISC Steel Design Guide 11 Floor vibrations due to human activity [23]) for the optimization process of two composite floor examples. His work was used as a reference for another research performed by Kaveh and Ghafari [191] where it was concluded that the vibrations were one of the critical LSs when designing a floor bay of 8 m  $\times$  10 m. Yossef and Taher [192] performed another cost optimization of composite floors with castellated beams using a widely accepted methodology to check the VSLs (the SCI guideline Design of floors for vibration [24]). In recent years, with the rise of life-cycle assessment, many authors have started to include the EC (measured in kgCO<sub>2</sub>eq) of the floor as an OF to optimize. Roynon [5] has presented a manual optimization of framed buildings minimizing their EC and giving reference values of kgCO<sub>2</sub>eq/m<sup>2</sup> for steel framed floors (between 80—250 kgCO<sub>2</sub>eq/m<sup>2</sup> for regular spans and 150—300 kgCO<sub>2</sub>eq/m<sup>2</sup> for long-span floors). Drevniok et al. [193] have developed an optimization methodology called 'The Lightest Beam Method' to study the amount of material that could have been reduced in a set of already designed and built steel floors without composite action. They consider the VSLs as a limitation in the natural frequency of 3 Hz, without assessing in detail the level of vibration. They concluded that the relaxation of serviceability requirements at the design stage could enable a reduction by more than 30% of the floors' weight. Some authors as Whitworth and Tsavdaridis [194] and Kravanja et al. [195] have used the embodied energy (measured in J) to quantify the environmental impact of the floors. Finally, in the research performed by Gauch et al. [196] different structural types of floors (made of concrete, steel, and timber) are designed and compared in terms of cost and EC obtaining interesting conclusions especially applicable to a decision-making stage of the design process. They again consider the VSLs by imposing a limit on the floor fundamental frequency of 4 Hz.

As a conclusion, it is clear that the VSLs should be properly taken into account in terms of the floor's acceleration response according to currently accepted guidelines as [23], [24] or [43]. Thus, to the author's knowledge, this study is the first one addressing the multi-objective optimization (with the floor's Weight and its EC as OFs) of composite floors designed with and without integrated CLD treatments, and including a detailed verification of the VSLs.

The remainder of this Chapter is organized as follows: Section 6.2 describes the

elements of the type of composite floors to be optimized. Section 6.3 outlines all the static limit states to be checked along the floor design. Section 6.4 explains the workflow used to check the VSLs and how the CLD treatment has been optimally designed for each analyzed case. Section 6.5 portrays the multi-objective structural optimization carried out describing the optimization procedure, the Ofs, and the optimization parameters used. Section 6.6 describes a parametric study in which different square floor bays with different spans have been optimized with and without the use of CLD treatments to illustrate the proposed methodology. Finally, Section 6.7 provides some conclusions.

## 6.2 Description of a composite floor with integrated CLD treatment

A composite floor with a given total length  $L$  and a total width  $B$  can be composed of different bays as represented in Figure 6.1. A bay is defined as a floor part between 4 columns and is composed of primary ( $1^{ry}$ ) beams spanning between columns and secondary ( $2^{ry}$ ) beams that span between these first ones. There are 3 types of bays depending on their location, (i) corner bays, (ii) edge bays, and (iii) internal bays. The first two groups are usually more prone to vibrate as they cannot mobilize as much mass when vibrating as the internal bays.

In this Section, the design of a composite floor with integrated CLD treatments is carried out according to the floor bay depicted in Figure 6.2. A given floor bay is geometrically defined by the length of its  $1^{ry}$  and  $2^{ry}$  beams, here known as  $L_1$  and  $L_2$ , respectively; the number of  $2^{ry}$  beams  $N_2$  and the distance between them  $d_2$ . The steel members of the floor are here defined through profile sections from the Universal Beam (UB) series (this catalog was chosen as it is large enough so that a meaningful optimization can be carried out). The profiles are represented with the integer values  $P_1$  and  $P_2$  which correspond with the profile positions in the UB catalog sorted according to the moment of inertia. S-275 steel has been considered. The concrete slab of the floor is defined by two parameters, (i) the commercial rib-deck used for the floor, which is defined with the integer value  $Rd$  (according to its position on the list of Cofraplus 60 rib-decks, with 4 different gauge thicknesses of 0.7 mm; 0.9 mm; 1 mm and 1.2 mm), and, (ii) the concrete slab thickness over the ribs in centimeters represented with the integer value  $h_c$ . The concrete grade used is C-30. Steel studs have been included along the central region of the  $1^{ry}$  and  $2^{ry}$  beams to ensure a certain degree of shear connection between the steel

members and the concrete slab. In the 1<sup>st</sup> beams, the separation of studs depends on the required bending resistance of the composite section at mid-span. In the 2<sup>nd</sup> beams their separation is equal to the distance between the valleys of the rib-deck. Ductile shear studs made of steel with a diameter of 19 mm, an as-welded height of 95 mm, and an ultimate limit stress of  $f_u = 450$  Mpa, have been considered.

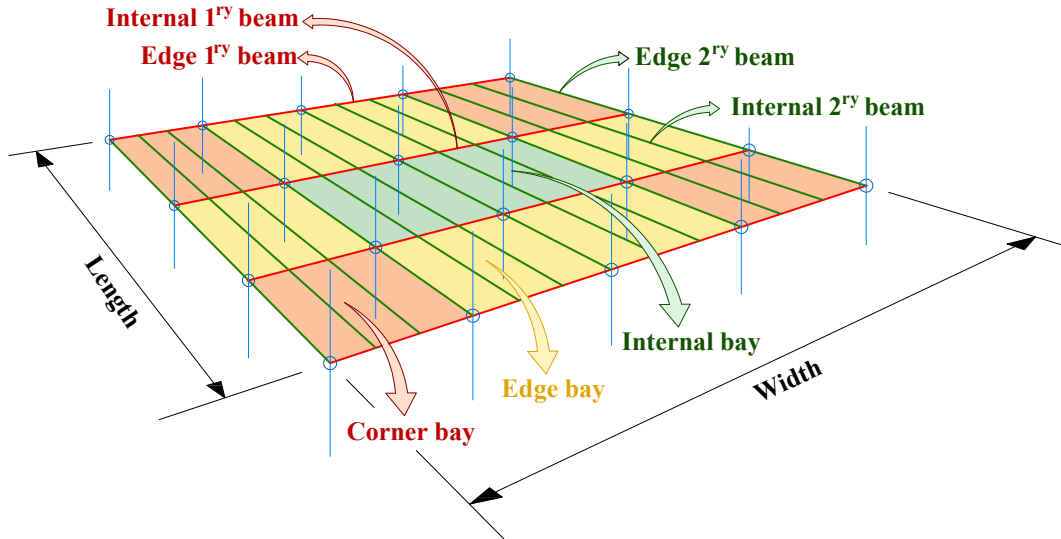


Figure 6.1: Scheme of a floor layout composed of bays.

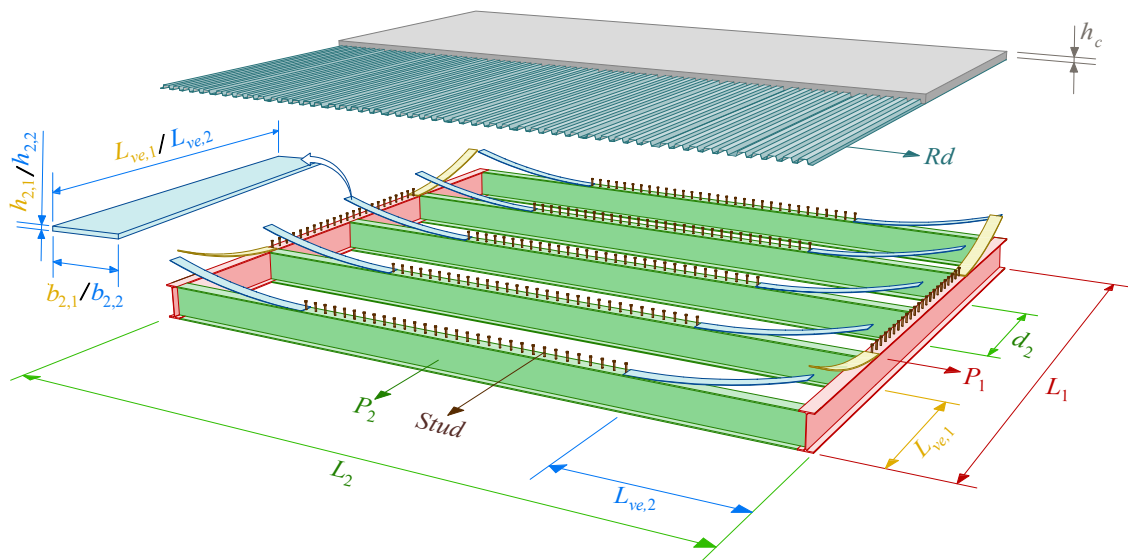


Figure 6.2: Elements of a floor bay with an integrated CLD treatment.

The CLD treatment has been included in all beams along a given length,  $L_{ve,i}$ , near the supports (being “ $i$ ” an index used to refer the 1<sup>st</sup> or 2<sup>nd</sup> beam). Thus, the percentages of beam” length treated with CLD are obtained as  $\%CLD_i = 100 \lambda_i$ , where  $\lambda_i$  is obtained as follows:

$$\lambda_i = (2 L_{ve,i})/L_i. \quad (6.1)$$

The thickness of the VE layer of these CLD treatments,  $h_{2,i}$ , needs to be small so three possible values of 0.5 mm; 1.0 mm and 2 mm have been considered for this parameter based on [171]. Moreover, the width of these VE layers,  $b_{2,i}$ , should be similar to the width of the top flange of their correspondent beams,  $b_{f,i}$ . For that reason,  $b_{2,i}$  must take a value within the continuous range that goes from  $0.5 b_{f,i}$  to  $2 b_{f,i}$ . The properties assigned to the VE material of the CLD treatment are in the range of commercial VE materials for vibration damping (for example, the HIP2, before cited [171]) i.e., a storage shear modulus  $G'_2$  of 0.5 MPa, a loss factor  $\eta_{2,ve}$  with a value of 1 and a density of 1700 kg/m<sup>3</sup>. The loss factor of this type of material is usually measured based on the standard testing method ASTM:E756-05 [197].

In Table 6.1 the main material properties used along the Chapter are listed indicating, the name of the material, the element in which it is used, and its main mechanical properties.  $\rho$  is used to denote the density of the material,  $E_{st}$  for the Young modulus of the steel,  $E_c$  for the Young modulus of the concrete,  $f_y$  is the yielding strength of the steel, and  $f_u$  is the ultimate tensile strength of the steel.

**Table 6.1** Material properties of the floor.

Material	Element	$\rho$ [kg/m <sup>3</sup> ]	$E_{st}$ [GPa]	$f_y$ [MPa]
Steel S275	Profiles	7850	210	275
Steel B500S	Reinforcement	7850	210	500
Steel S350GD	Rib-deck	7850	210	350
		$\rho$ [kg/m <sup>3</sup> ]	$E_{st}$ [GPa]	$f_u$ [MPa]
Steel S235J2+	Shear studs	7850	190	450
		$\rho$ [kg/m <sup>3</sup> ]	$E_c$ [GPa]	$f_{ck}$ [MPa]
Concrete C30	Slab	2500	30	30
		$\rho$ [kg/m <sup>3</sup> ]	$G'_2$ [MPa]	$\eta_{2,ve}$ [-]
HIP2	CLD treatment	1700	0.7	1

In this study, for given a floor bay defined by a set of  $L_1$  and  $L_2$ , the rest of the floor parameters above described ( $P_1$ ,  $P_2$ ,  $N_2$ ,  $h_c$ ,  $R_d$ ,  $L_{ve,1}$ ,  $L_{ve,2}$ ,  $h_{2,1}$ ,  $h_{2,2}$ ,  $b_{2,1}$  and  $b_{2,2}$ ) are optimized to minimize two OFs, while meeting all the LSs of the floor design.

## 6.3 Static LSs to be met by the floor

### 6.3.1 Static LSs in the 1<sup>ry</sup> and 2<sup>ry</sup> beams

All the beams of the floor are designed as simply supported and built without any propping system. Hence, two design stages have been verified: (i) the construction and (ii) the service life of the floor. The LSs checked in the 1<sup>ry</sup> and 2<sup>ry</sup> beams are summarized in Table 6.2. Each LS is defined through a safety factor  $SF$ , which, if higher than 1, means that LS is met. To identify each  $SF$ , a set of three subscripts separated by commas has been used:


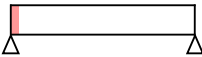
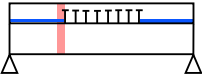
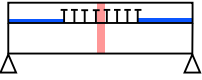

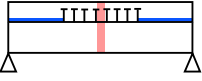
- *Subscript 1* identifies the variable used to compute the safety factor. The following options are available: ‘ $M+$ ’ means the sagging bending moment at mid-span, ‘ $M+B$ ’ means the sagging bending moment at the location of the first shear stud in partially treated beams, ‘ $Q$ ’ denotes shear force at the support, and ‘ $\delta LL$ ’ means deflection under live load action.
- *Subscript 2* may be ‘ $c$ ’ or ‘ $s$ ’ depending on if the LS belongs to the construction stage or to the service-life stage, respectively.
- *Subscript 3* is the subscript ‘ $i$ ’ used to denote the 1<sup>ry</sup> or 2<sup>ry</sup> beam.

#### Static LSs of 1<sup>ry</sup> and 2<sup>ry</sup> beams: the construction

The loads considered here are the self-weight,  $SW_c$  and a construction live load  $LL_c = 0.75 \text{ kN/m}^2$ . At this stage, the concrete is not a resisting element and it has a fresh density of  $2500 \text{ kg/m}^3$ .

The verification has been done according to Eurocode 3 [103], as the only resisting element is the steel member of the floor. The Ultimate LS (ULS) of bending at mid-span has been checked concerning the plastic bending moment of the steel section,  $M_{p,st}$ , and

**Table 6.2** Static LSs checked in the 1<sup>ry</sup> and 2<sup>ry</sup> beams of the floor with integrated CLD treatment.

Stage	Limit State	Type	Location	Loads	Section	Safety Factor
Construction	ULS	Bending		$SW + LL_c$	Steel	$SF_{M+,c,i}$
		Shear		$SW + LL_c$	Steel	$SF_{Q,c,i}$
Service-Life	ULS	Bending		$SW + DL + LL_s$	Steel	$SF_{M+B,s,i}$
		Bending		$SW + DL + LL_s$	Composite	$SF_{M+,s,i}$
		Shear		$SW + DL + LL_s$	Steel	$SF_{Q,s,i}$
	SLS	Deflection		$LL_s$	Composite	$SF_{\delta LL,s,i}$

the ULS of shear at the support section with respect to the plastic shear of the steel web,  $Q_{p,st}$  (with the subscript ‘ $p$ ’ indicating plastic and ‘ $st$ ’ indicating steel).

### Static LSs of 1<sup>ry</sup> and 2<sup>ry</sup> beams: the service life

The loads considered at this stage are the self-weight  $SW_s$  of the structural elements, (but now using a dried density for the concrete of  $2400 \text{ kg/m}^3$ ), a deal load  $DL_s$  for flooring finishes of  $1 \text{ kN/m}^2$  and a live load  $LL_s$  of  $3 \text{ kN/m}^2$ .

The verification has been performed following Eurocode 4 [178], as the concrete slab is now a resisting element of the beam section. Four LSs have been checked at this stage, (i) the ULS of bending at the end of the CLD treatment, where the fist shear stud is located (ii) the ULS of bending at mid-span, (iii) the ULS of shear, verified only considering the resisting contribution of the web of the steel member, and (iv) the deflection serviceability LS (DSLS) at mid-span under the action of  $LL_s$ , which has been limited to  $L_i/350$ . Special attention must be paid to the verification of the ULS of bending and the DSLS of composite

beams partially treated with CLD along their length.

### ULS of bending for composite beams partially treated with CLD

Here, the concepts previously introduced in Section 4.4.1 of Chapter 4 will be explained in more detail.

In a regular simply supported composite beam, the ULS of bending is verified by assuring that the resisting moment of the composite section at mid-span  $M_{Rd,comp}$  is higher than the service life acting design bending moment  $M_{Ed,s}$ . This criterion is not sufficient for partially treated beams as the most critical section for bending may lie somewhere in between the first section connected to the shear and the mid-span section. This can be seen in Figure 6.3, where the bending resisting envelopes of a 15 m secondary beam treated with different %CLD have been compared with the laws of maximum design bending moment. It can be noted that along the CLD-treated length, the resisting bending moment is the one provided by the steel member,  $M_{Rd,st}$ , whereas, along the shear-connected central length its value increases due to the composite action. A simplified methodology to avoid checking the ULS of bending along the whole beam length has been developed based on checking two critical sections, (i) the mid-span and (ii) the first shear-connected section, here called Section B. A similar simplification was performed by Willford et al. [8]; However, in this contribution, it was assumed a degree of shear connection along the central connected region of 60% and it did not provide a detailed explanation of how this ULS should be computed. A more accurate description of this verification is provided below with adequate assumptions.

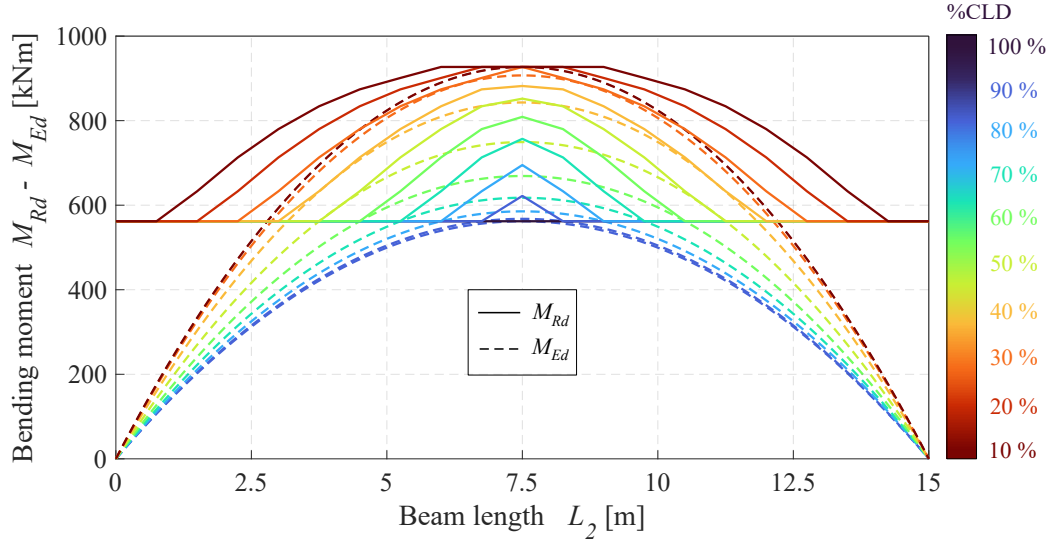
For checking the Section B the design bending moment at this section has been compared to the plastic bending moment of the steel member,  $M_{p,st}$ .

To verify the mid-span section the following considerations have been made:

- The effective breadth of the slab,  $b_{eff,i}$ , contributing to the composite section has been computed as follows:

$$b_{eff,1} = \min \left\{ \begin{array}{c} (L_1 - 2L_{ve,1})/4 \\ L_2 \end{array} \right\}, \quad (6.2)$$

$$b_{eff,2} = \min \left\{ \begin{array}{c} (L_2 - 2L_{ve,2})/4 \\ d_2 \end{array} \right\}. \quad (6.3)$$



**Figure 6.3:** Envelopes of resisting bending moment,  $M_{Rd}$ , compared to the laws of maximum design bending moment,  $M_{Ed}$ , for different %CLD treatment.

The expression used here is the same one as for regular simply supported composite beams, but replacing the beam length by the shear-connected length,  $L_{conn,i} = (L_i - 2 L_{ve,i})$ . This decision is proposed by the author as it is on the safe side.

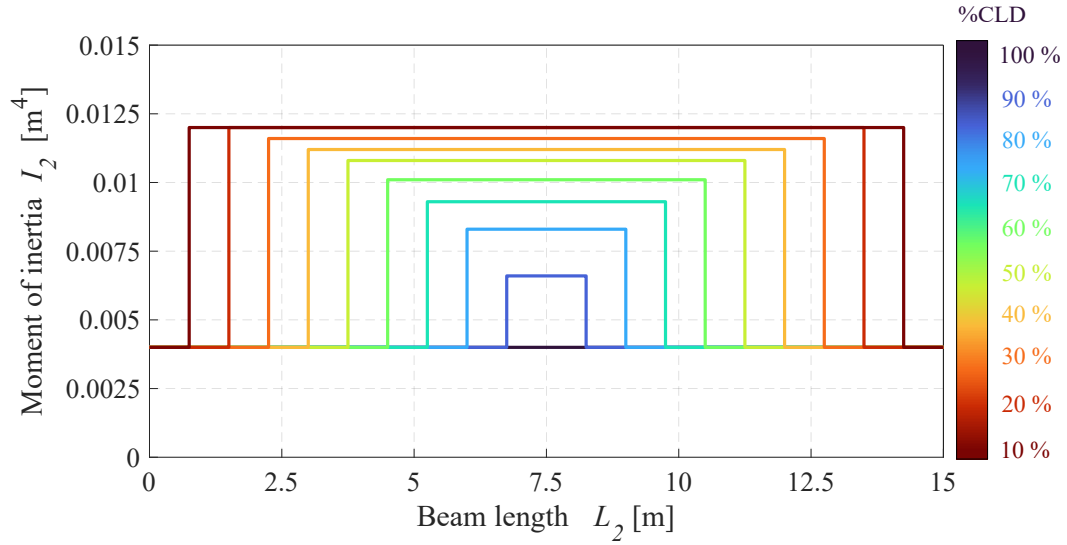
- Two ductile shear studs per section connected have been used to achieve a higher degree of shear connection in a shorter distance. Additionally, plastic redistribution of longitudinal shear forces between the different shear studs along the connected length has been assumed.
- Partial shear connection theory has been assumed. Hence, the maximum longitudinal shear to be transferred within the steel–concrete interface,  $N_c$  is limited by the plastic capacity of the shear connection. This means that the maximum longitudinal shear when considering full shear connection, named  $N_{cf}$ , needs to be reduced by a factor  $\alpha$  called 'degree of shear connection' which is computed as follows:

$$\alpha = \frac{P_{rd}(n/2)}{N_{cf}}, \quad (6.4)$$

$$N_c = \alpha N_{cf}, \quad (6.5)$$

where  $P_{rd}$  is the shear resisting value of a single shear stud and  $n$  is the total number of shear studs along the shear-connected length of the beam.

Finally, the resisting bending moment at mid-span has been computed following the methodology given in Eurocode 4 [178].



**Figure 6.4:** Equivalent moments of inertia homogenized to the concrete used to compute the deflection of beams with different %CLD treatment.

### DSLS for composite beams partially treated with CLD

The author propose the use of two bending stiffnesses along the beam length (see Figure 6.4): (i) the stiffness of the steel member for the CLD-treated region, and (ii) the bending stiffness of the composite section considering full-composite action (i.e., an infinitely rigid shear connection) and the cracking of the concrete slab. The slab” effective breadth used has been the same as the one described for the ULS given in Equations (6.2) and (6.3).

### 6.3.2 Static LSs in the rib-deck slab

The rib-deck slab has been analyzed as a multi-span beam with as many supports as secondary beams are used within a floor bay. Again, two stages have been checked: (i) the construction and, (ii) the service life of the rib-deck. Table 6.3 summarizes the set of LSs checked in the rib-deck slab.

Again, each LS is related to a  $SF$  defined with a set of two subscripts:

- *Subscript 1* defines the variable used to compute the  $SF$ : ‘ $M+$ ’ refers to the sagging bending moment at the edge span of the slab, ‘ $M-$ ’ denotes the hogging bending

moment at the internal support of the edge span, ‘ $Q$ ’ means the shear force at the internal support of the edge span, ‘ $\delta LL$ ’ means the maximum deflection under the live load action at the edge span, and ‘ $\delta SW$ ’ indicates the maximum deflection under the self-weight action at the edge span.

- *Subscript 2* again may be ‘ $c$ ’ or ‘ $s$ ’ depending on the stage analyzed.

**Table 6.3** Static LSs checked in the rib-deck slab of the floor.

Stage	Limit State	Type	Location	Loads	Section	Safety Factor
Construction	ULS	Bending		$SW + LL_c$	Steel	$SF_{M+,c}$ $SF_{M-,c}$
		Shear		$SW + LL_c$	Steel	$SF_{Q,c}$
	SLS	Deflection ponding		$SW + LL_c$	Steel	$SF_{\delta LL,c}$
Service-life	ULS	Bending		$SW + DL + LL_s$	Composite	$SF_{M+,s}$ $SF_{M-,s}$
		Shear		$SW + DL + LL_s$	Composite	$SF_{Q,s}$
	SLS	Deflection		$LL_s$	Composite	$SF_{\delta LL,s}$

**Static LSs in the rib-deck Slab: the construction**

No propping system has been considered during the construction, hence, the only resisting element in this stage is the steel decking. The same loads considered for the beam” verification have been used here. Four LSs have been checked, (i) the ULS of the sagging bending moment in the edge span, (ii) the ULS of the hogging bending moment in the second support, (iii) the ULS of shear in the second support (for this case, the crippling of the steel decking webs has been considered to be the most restrictive shear failure mode) and, (iv) the SLS of deflection in the edge span during the concreting process limited to

$d_2/180$  to control the ponding effect. In each case, the construction live load was assumed to be present in the worst spans. The resisting parameters of the steel decking have been taken from the Cofraplus 60 technical sheets.

### **Static LSs in the rib-deck slab: the service life**

During the service life, the composite section of the rib-deck slab must be verified. The same four LSs as for the construction stage have been checked but considering the resisting parameters of the composite section: (i) the ULS of sagging bending moment. For computing the resisting moment no reinforcement has been used, and the contribution of the steel decking has been accounted through using a degree of shear connection with the concrete (as done before with the beam” shear connection). The limit shear tension within the steel–concrete interface has been assumed to be 0.1 MPa [198]. (ii) The ULS of hogging bending moment. For computing the resisting moment, the contribution of the steel decking has been neglected, thus, a regular reinforced concrete section has been analyzed. An appropriate hogging reinforcement has been sized for each case being extended over a length equal to  $d_2/3$  from the supports. To obtain both the acting sagging and hogging bending moments, a redistribution due to cracking of the bending law of a 15% has been assumed. (iii) The ULS of shear. The resisting shear of the composite slab has been obtained as a result of two contributions, the shear resistance of the steel decking and the shear resistance of the concrete ribs without any shear reinforcement. (iv) The DSLS. The deflection at the edge span under the action of the worst live load placing has been computed as the average value between those obtained with and without considering cracking in the concrete. This has been limited to  $d_2/350$ .

## **6.4 VSLS of floors partially treated with CLD**

As was previously done for the application example developed in Section 4.5 of Chapter 4, The VSLS of the floor has been assessed according to the simplified methodology provided by the AISC Steel Design Guide 11 [23]. The AISC method quantifies the vibration in terms of peak acceleration; however, this Section provides equivalent root mean square (rms) acceleration values, as these enable obtaining the response factors widely used in other guidelines and in future versions of Eurocodes to establish vibration limits. In this section, first, a simplified methodology to compute the fundamental modal parameters of a floor bay treated with CLD is given. Then, the dynamic response of the floor bay is

computed similarly as it was done in the application example of Chapter 4.

### 6.4.1 Fundamental modal parameters of the floor

#### Fundamental natural frequency of the Floor

The fundamental natural frequency of a floor bay,  $f_n$ , has been obtained by computing the fundamental natural frequencies of the primary and secondary beams from the maximum static deflections,  $\delta_1$  and  $\delta_2$ , under the floor's weight considered for the VSLS, and then applying the Dunkerle's approximation as follows:

$$f_n = \frac{18}{\sqrt{1000 (\delta_1 + \delta_2)}}. \quad (6.6)$$

These deflections have been computed considering a load per unit of length for each beam,  $q_{VSLS,i}$ , equal to:

$$q_{VSLS,i} = q_{SW,i} + q_{DL,i} + 0.1 q_{LL,i}, \quad (6.7)$$

where  $q_{SW,i}$ ,  $q_{DL,i}$  and  $q_{LL,i}$  are the self-weight, dead load, and live load per unit of length of the beam, respectively. Then, the following expression has been derived to compute the deflection of a partially CLD-treated beam. The author proposes to apply the Maxwell-Mohr method to the law of elastic curvatures of a simply supported beam, with two different bending stiffnesses and uniformly loaded:

$$\delta_i = \frac{L_i^4 q_{VSLS,i}}{384} \left[ \frac{-3\lambda_i^4 + 8\lambda_i^3}{E_{st} I_{st,i}} + \frac{3\lambda_i^4 - 8\lambda_i^3 + 5}{E_c I_{c,i}} \right], \quad (6.8)$$

where  $E_{st}$  and  $E_c$  are the Young modulus of the steel and the concrete, respectively;  $I_{st,i}$  is the moment of inertia of the steel profile used for the beams, and  $I_{c,i}$  is a concrete-homogenized moment of inertia of the composite section present along the shear-connected region of the beam.  $\lambda_i$  is the proportion of CLD-treated beam in parts per unit computed in Equation (6.1). For 1<sup>st</sup> beams just supporting one 2<sup>nd</sup> beam at mid-span,  $\delta_1$  has been increased by a factor of 1.3.

### Effective weight of the floor's fundamental mode of vibration

This magnitude has been computed following the AISC Design Guideline 11 as follows. This method is composed of 3 steps:

1. Computing the effective widths,  $B_{eff,1}$  and  $B_{eff,2}$ , respectively associated with the simply supported bending modes of the 1<sup>ry</sup> and 2<sup>ry</sup> beams of the floor, following an already calibrated formulation described below:

$$B_{eff,1} = L_1 \left[ C_1 \left( \frac{I_{eff,2}/d_2}{I_{eff,1}/L_2} \right)^{1/4} \right] < L, \quad (6.9)$$

$$B_{eff,2} = L_2 \left[ C_2 \left( \frac{I_{slab}}{I_{eff,2}/d_2} \right)^{1/4} \right] < B, \quad (6.10)$$

where  $I_{slab}$  is the concrete-homogenized moment of inertia of one meter of composite rib-deck slab,  $C_1$  and  $C_2$  are calibration coefficients depending on the type of composite floor beams and floor bay to be analyzed, and  $I_{eff,1}$  and  $I_{eff,2}$  are the effective concrete-homogenized moments of inertia of the 1<sup>ry</sup> and 2<sup>ry</sup> beams, respectively. They have been computed as follows:

$$I_{eff,i} = \frac{L_i^4}{384} \frac{5 q_{VSLs,i}}{E_c \delta_i}. \quad (6.11)$$

2. Computing the effective weights,  $W_{eff,1}$  and  $W_{eff,2}$ , respectively associated with the simply supported bending modes of the 1<sup>ry</sup> and 2<sup>ry</sup> beams:

$$W_{eff,1} = \frac{B_{eff,1}}{2} \frac{L_1 q_{VSLs,1}}{L_2}, \quad (6.12)$$

$$W_{eff,2} = K_2 \frac{B_{eff,2}}{2} \frac{L_2 q_{VSLs,2}}{d_2}, \quad (6.13)$$

where  $K_2$  is a factor equal to 1.5 for floor bays with adjacent bays having secondary beams of length higher than 0.7  $L_2$ , and equal to 1 in other cases.

3. Computing the final effective weight  $W_{eff}$  of the combined mode of vibration:

$$W_{eff} = W_{eff,1} \frac{\delta_1}{\delta_1 + \delta_2} + W_{eff,2} \frac{\delta_2}{\delta_1 + \delta_2}. \quad (6.14)$$

### Intrinsic damping ratio of the floor's fundamental mode of vibration

Two main sources of damping contribute to defining the final value of the fundamental modal damping ratio,  $\xi_n$ . These are: (i) the intrinsic damping of the structure,  $\xi_{int}$  (the usual source of energy dissipation that depends on the type of floor structure, the floor finishes, and the furniture present on the floor) and, (ii) the additional damping ratio provided by the VE CLD treatment,  $\xi_{CLD}$ . Thus, the following equation has been used:

$$\xi_n = \xi_{int} + \xi_{CLD}. \quad (6.15)$$

$\xi_{int}$  has been computed assuming an electronic office fit-out with ceiling and ductwork. Hence, according to the AISC guideline,  $\xi_{int} = 0.01 + 0.01 + 0.005 = 0.025$ .

### Additional damping ratio provided by the CLD treatment

In this study,  $\xi_{CLD}$  has been computed using a simplified new methodology proposed by the author based on solving the problem of a simply supported 'sandwich beam' partially treated with a VE core. This method is divided into 4 sub-steps.

1. Obtain  $N_1$  and  $N_2$ , the number of 1<sup>st</sup> and 2<sup>nd</sup> beams involved in the fundamental mode of vibration, respectively. This is performed using the effective widths,  $B_{eff,i}$  computed before, assuming that they define the effective floor area contributing to the vibration when assessing the VSLS:

$$N_1 = \left( \frac{B_{eff,1}}{L_2} + 1 \right) \left( \frac{B_{eff,2}}{L_1} \right), \quad (6.16)$$

$$N_2 = \left( \frac{B_{eff,2}}{d_2} + 1 \right) \left( \frac{B_{eff,1}}{L_2} \right). \quad (6.17)$$

2. Compute the additional damping ratio,  $\xi_{CLD,i}$ , provided by the applied CLD treatments to isolated 1<sup>st</sup> and 2<sup>nd</sup> beams. This has been done by analyzing a simply supported beam partially treated with CLD and characterized by the following parameters  $L_i$ ,  $L_{ve,i}$ ,  $P_i$ ,  $R_d$ ,  $h_c$ ,  $b_{eff,i}$  and with a CLD treatment defined by  $h_{2,i}$  and  $b_{2,i}$ .

The value of  $\xi_{CLD,i}$  depends on four dimensionless parameters:

- $\eta_{2,ve}$ , the loss factor of the VE material, the higher  $\eta_{2,ve}$  the better. In this study, this parameter has been assumed to be constant and equal to 1.
- %CLD the percentage of the beam length treated with CLD. The higher this parameter, the higher the damping enhancement.
- $Y$ , the geometric parameter, here computed as the ratio between the following two bending stiffnesses:

$$Y = \frac{(E_c I_{c,i})}{(E_{st} I_{st,i})}. \quad (6.18)$$

where the numerator and denominator are the bending stiffnesses of a 100% CLD beam where the VE core has been replaced by a shear connection with infinite or zero shear stiffness, respectively. This ratio oscillates between 1 and 3 for composite floor beams, as can be checked by looking through the Tables 4.2 and 4.3 developed in Chapter 4. The higher the  $Y$ , the higher the damping.

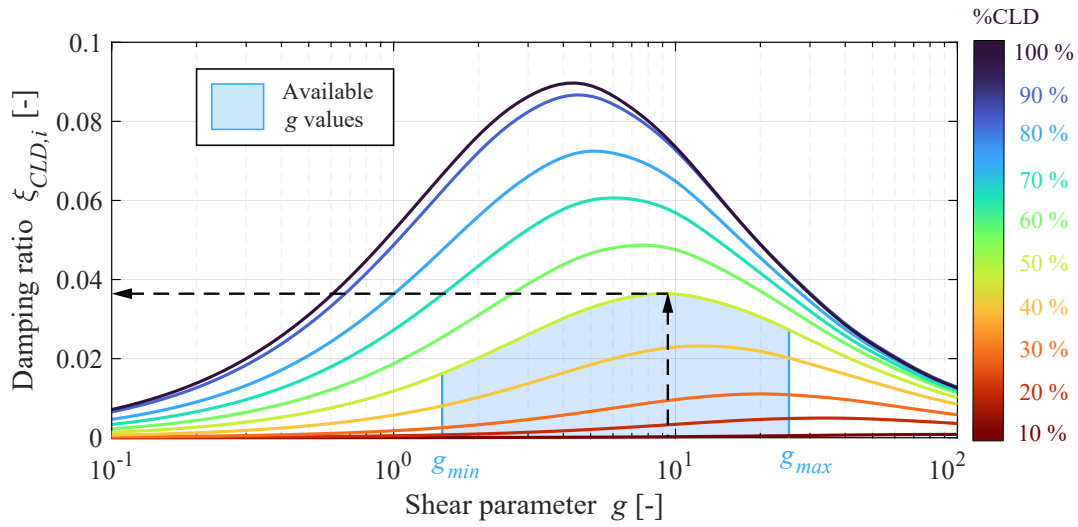
- $g$ , the shear parameter of the beam, (it should be noted that  $g$  is strongly dependent on the parameters of the VE treatment). This parameter has been here computed by adapting the formula previously introduced in Equation 3.32:

$$g = G_2' \frac{b_{2,i} L_i^2 (E_{st} A_{st,i} + E_c A_{slab,i})}{h_{2,i} E_{st} A_{st,i} E_c A_{slab,i}}, \quad (6.19)$$

where  $A_{st,i}$  and  $A_{slab,i}$  are the areas of the profile and the slab that belong to the beam section to be analyzed, respectively.

For each beam, there is an optimum  $g_{opt}$  that provides the maximum additional damping to the beam. The value of  $g_{opt}$  depends on  $Y$ ,  $\eta_{2,ve}$  and %CLD of the beam as has been previously demonstrated in Chapters 3 and 4. The dependency of  $g_{opt}$  with  $Y$  can be neglected in the range of  $Y$  values adopted by floor beams. This has been previously evidenced in the parametric study developed in Section 4.4 of Chapter 4, more specifically in Figure 4.11.(e). In the same way, the VE materials used for this purpose have similar values of  $\eta_{2,ve}$  close to 1, so this dependency can be also neglected.

Knowing this, the author has proposed a simplified methodology to obtain  $\xi_{CLD,i}$ , assuming that it depends only on  $g$  and %CLD.  $\xi_{CLD,i}$  has been obtained using the set of curves depicted in Figure 6.5.



**Figure 6.5:** Set of design curves used to compute  $\xi_{CLD,i}$  in a simply supported isolated beam of the floor. Results obtained in the parametric analysis developed in Section 4.4 for beams with 15 m span analyzed with the approach M1-CMA.

These curves have been obtained from the parametric analysis of CLD-treated beams previously developed in Section 4.4 of Chapter 4. More specifically, the set of curves provided in Figure 6.5 corresponds to the results obtained for beams with 15 m of span using the modelling approach M1-CMA. As a reminder, this means that the beams have been accurately modelled in ANSYS software, using SOLID185 elements for the rib-deck slab and the VE layer, and SHELL181 elements for the steel profile. Finally, CMA has been used to obtain the additional damping provided by the CLD treatment. The decision to use the results obtained for beams with a length of 15 m (and not another length) was adopted to be on the safe side. Looking at the optimal results of this previous parametric study, shown in Figure 4.11, it is evident that the beams with 15 m length were those with lower values of  $\eta_{max}$  (Figure 4.11.(c)). In addition, the values of  $g_{opt}$  were quite similar independently on the beam length tested (Figure 4.11.(e)), so the optimal design of the CLD configuration is not compromised by taking this decision.

Knowing this and given a partially treated floor beam, the geometry of the CLD treatment is designed by selecting the right values of  $h_{2,i}$  and  $b_{2,i}$  within the available ones, to provide a shear parameter as close as possible to  $g_{opt}$ , as shown in Figure 6.5 for a 50 %CLD beam.

3. Compute the bending modal strain energy,  $V_{bend,i}$  of isolated 1<sup>ry</sup> and 2<sup>ry</sup> beams of

the floor bay analysed, as follows:

$$V_{bend,i} = \frac{1}{2} \int_0^{L_i} \left( \frac{M_{VSLS,i}(s)^2}{E(s)I(s)} \right) ds, \quad (6.20)$$

where  $M_{VSLS,i}(x)$ ,  $E(x)$  and  $I(x)$  are the laws of bending moments (under the loads considered for the VSLS), Young modulus, and Moment of inertia along the beam length. Assuming the scheme of a simply supported beam uniformly loaded and divided into two regions of different inertia, the following expression is derived:

$$V_{bend,i} = \frac{q_{VSLS,i}^2 L_i^5}{1920} \left( \frac{3 \lambda_i^5 - 15 \lambda_i^4 + 20 \lambda_i^3}{E_{st} I_{st,i}} - \frac{3 \lambda_i^5 - 15 \lambda_i^4 + 20 \lambda_i^3 - 8}{E_c I_{c,i}} \right). \quad (6.21)$$

- 4 Calculate the final  $\xi_{CLD}$  of the floor's fundamental mode of vibration as a weighted value of  $\xi_{CLD,1}$  and  $\xi_{CLD,2}$  depending on their contribution to the total modal strain energy of the floor. This means applying the MSE method to compute  $\xi_{CLD}$ . In this case, the error committed by using the MSE is negligible because none of the elements providing damping to the overall system has a big damping value. Therefore, the MSE is being used in the range in which its linear prediction is accurate (Figure 4.4). The following equation is used to compute  $\xi_{CLD}$ :

$$\xi_{CLD} = \frac{\xi_{CLD,1} N_1 V_{bend,1} + \xi_{CLD,2} N_2 V_{bend,2}}{N_1 V_{bend,1} + N_2 V_{bend,2}}. \quad (6.22)$$

## 6.4.2 Dynamic response of the floor

For checking the VSLS, two types of dynamic floor responses have been computed under walking excitation according to the methodology given by [23]: (i) the resonant response of vibration modes with frequencies lower than 9 Hz, obtaining a response factor  $R_{res}$  and (ii) the impulsive transient response produced by a footfall excitation, obtaining a response factor  $R_{imp}$ .

The computation of response factors,  $R_{res}$  and  $R_{imp}$  has been performed using the same formulations previously exposed in Sections 4.5.1 and 4.5.2 of Chapter 4, respectively. There are only two minor discrepancies:

- When calculating  $R_{res}$  the parameter  $R_{calres}$  has been assumed to be equal to 0.5 (not 0.7), as the floor bay analyzed is a two-way span system, not a one-way span system as occurred in the examples analyzed in Chapter 4.

- When obtaining  $R_{imp}$ , the higher mode factor  $R_M=2$  (before used in Chapter 4), has not been used in this study. This parameter, to the author's knowledge, is over-conservative and, indeed, it is not used in other guidelines as [43].

### Comparison with VSLS limits

A limiting response factor,  $R_{lim}$ , must be set depending on the vibration comfort level required by the floor use. Hence, two possible safety factors for checking the VSLS can be built: (i)  $SF_{Rmax,s}$  when considering checking both the resonant and impulsive responses, and (ii)  $SF_{Rres,s}$  when only checking the resonant response of the floor:

$$SF_{Rmax,s} = \frac{\max(R_{res}, R_{imp})}{R_{lim}}, \quad (6.23)$$

$$SF_{Rres,s} = \frac{R_{res}}{R_{lim}}. \quad (6.24)$$

## 6.5 Optimization problem definition

In this section, the author proposes the definition of an optimization problem for the structural design of composite floors partially treated with CLD. The floor optimization addressed is a discrete multi-objective optimization problem with two OFs ( $f_1(\underline{x})$  and  $f_2(\underline{x})$ ) depending on a vector  $\underline{x}$  of seven design variables defined by integer numbers (from  $\underline{x}_1$  to  $\underline{x}_7$ ), and with six design constraints defined by the functions  $g_1(\underline{x})$  to  $g_6(\underline{x})$ . The optimization problem can be formulated as follows:

$$\begin{aligned}
& \min f_1(\underline{x}) = M(\underline{x}) \\
& \min f_2(\underline{x}) = EC(\underline{x}) \\
& \text{s.t. } g_1(\underline{x}) = ULS_1(\underline{x}) \leq 0 \\
& \quad g_2(\underline{x}) = ULS_2(\underline{x}) \leq 0 \\
& \quad g_3(\underline{x}) = DSLS_1(\underline{x}) \leq 0 \\
& \quad g_4(\underline{x}) = DSLS_2(\underline{x}) \leq 0 \\
& \quad g_5(\underline{x}) = LS_{slab}(\underline{x}) \leq 0 \\
& \quad g_6(\underline{x}) = VSLS(\underline{x}) \leq 0 \\
& \quad 6 \leq \underline{x}_1 = h_c \leq 20 \\
& \quad 1 \leq \underline{x}_2 = Rd \leq 4 \\
& \quad 1 \leq \underline{x}_3 = P_1 \leq 94 \\
& \quad 1 \leq \underline{x}_4 = P_2 \leq 94 \\
& \quad 0 \leq \underline{x}_5 = 10 \lambda_1 \leq 10 \\
& \quad 0 \leq \underline{x}_6 = 10 \lambda_2 \leq 10 \\
& \quad 1 \leq \underline{x}_7 = (N_2 - 1) \leq 10 \\
& \quad \underline{x} \in \mathbb{Z},
\end{aligned} \tag{6.25}$$

where  $M(\underline{x})$  and  $EC(\underline{x})$  are the functions to compute the mass of a floor bay and its embodied upfront carbon per unit of floor area, respectively. Additionally,  $ULS_1(\underline{x})$ ,  $ULS_2(\underline{x})$ ,  $DSLS_1(\underline{x})$ ,  $DSLS_2(\underline{x})$ ,  $LS_{slab}(\underline{x})$  and  $VSLS(\underline{x})$  are aggregate functions of the LSs checked for the different floor elements, and are described in detail in the following subsection devoted to the constraints of the problem. They provide a value of 0 if the concerning LSs have been met and positive values if not.

### 6.5.1 Design Variables

The seven design variables are integers since the structural optimization of a floor is subjected to the adoption of discrete values on its geometrical parameters to ease the construction process of the floor.

The floor optimization performed assumes a given floor bay defined by fixed distances between columns  $L_1$  and  $L_2$  that belongs to a given floor with fixed total length ( $L$ ) and

fixed total width ( $B$ ). This bay is optimized by finding the optimal values of the following variables:  $h_c$ ,  $R_d$ ,  $P_1$ ,  $P_2$ ,  $10\lambda_1$ ,  $10\lambda_2$  and  $(N_2-1)$ . The remaining floor-defining parameters are obtained when checking the different LSs as follows:

- $n_i$ : the number of shear studs used in each beam is calculated to meet the bending ULS of the beam at mid-span.
- $b_{v,i}$  and  $h_{v,i}$ : the dimensions of the CLD treatment used in each floor beam are obtained to maximize the  $\xi_{CLD,i}$  of each beam.
- $\rho_{h,slab}$ : the amount of hogging reinforcement of the slab is computed to meet the ULS of the hogging bending moment of the slab.

### 6.5.2 Objective Functions

Two objective functions have been minimized: (i) The mass of the floor bay per unit of area,  $M(\underline{x})$ , and (ii) the embodied upfront carbon of the floor bay per unit of area,  $EC(\underline{x})$ . The choice of these two OFs is based on the fact that to tackle the vibration problem from the design perspective, two main strategies can be adopted: (i) to increase the mass of the floor, by thickening the concrete slab, which has a great impact on the floor's  $M(\underline{x})$  but not much in the  $EC(\underline{x})$ , or (ii) to stiffen the steel members of the floor, which increases much more the  $EC(\underline{x})$  than the  $M(\underline{x})$ . This stays true when using low-strength concrete (with low cement content) and non-recycled steel, as in this case the carbon factor of the steel is much higher than the concrete one.

The computation of  $EC(\underline{x})$  has been carried out according to the guideline 'How to Compute Embodied Carbon' by Gibbons et al. [199]. This study has only considered the influence of the embodied upfront carbon of the floor (i.e., from modules A1 to A5 of the floor's life-cycle). For the computation of  $EC(\underline{x})$ , the following floor elements have been considered: concrete slab, slab reinforcement, rib-deck sheet, steel beams, shear studs, and CLD treatment. Modules A1 to A3 (those belonging to the Product Stage of the life-cycle) are the main contributors to the final upfront EC of the floor. Thus, a list of the A1–A3 Carbon Factors used (denoted as  $ECF_{A1-A3,n}$ ) for the  $n$ th materials of the floor, is provided in Table 6.4.

**Table 6.4** Carbon Factors  $ECF_{A1-A3,n}$  used for the different materials of the floor.

Material	Floor Element	$ECF_{A1-A3,n}$ [kgCO <sub>2</sub> eq/kg]
Concrete	Slab	0.10 <sup>1</sup>
Steel	Reinforcement	0.76 <sup>1</sup>
Steel	Beam profiles	1.74 <sup>1</sup>
Steel	Studs	1.74 <sup>1</sup>
Galvanized Steel	Rib-deck sheet	2.87 <sup>1</sup>
Galvanized Steel	CLD Sheets	2.87 <sup>1</sup>
VE material	CLD VE core	6.00 <sup>2</sup>

<sup>1</sup> Recommended default values for projects in the UK given by Table 2.3 of [199].

<sup>2</sup> Assuming the use of a VE material similar to the natural or butyl rubber. Taken from [200].

The floor studied is supposed to be built in a UK city. The steel and concrete have been assumed to be provided by a national and a local supplier, through road transport of 300 km and 50 km, respectively. An 'A4 Carbon Factor' for road transport of 0.10749 gCO<sub>2</sub>eq/kg/km has been used.

### 6.5.3 Design Constrains

Six different design constraint functions have been used:  $ULS_1(\underline{x})$ ,  $ULS_2(\underline{x})$ ,  $DSLS_1(\underline{x})$  and  $DSLS_2(\underline{x})$  for the ULS and DSLS of 1<sup>st</sup> and 2<sup>nd</sup> beams, respectively;  $LS_{slab}(\underline{x})$  for all the LSs of the rib-deck slab, and  $VSLs(\underline{x})$  for the VSLS of the whole floor. These functions are built using safety factor functions  $SF(\underline{x})$  (that compute for a given floor configuration  $\underline{x}$ , all the  $SF$  listed in previous sections) in combination with the following Modified Heaviside function  $H(SF)$  (that gives a value of 0 if the  $SF$  value is lower than 1, and provides 1 if the input is greater or equal than 1):

$$\begin{aligned}
 H : \mathbb{R} &\rightarrow \{0, 1\} \\
 SF &\rightarrow H(SF) \\
 H(SF) &= \begin{cases} 1 & \text{if } SF \geq 1 \\ 0 & \text{if } SF < 1 \end{cases} .
 \end{aligned} \tag{6.26}$$

Thus, the constraint equations used are defined as follows:

$$ULS_i(\underline{x}) = 1 - [H(SF_{M+,c,i}(\underline{x})) + H(SF_{Q,c,i}(\underline{x})) + H(SF_{M+,s,i}(\underline{x})) + H(SF_{M+B,s,i}(\underline{x})) + H(SF_{Q,s,i}(\underline{x}))]/5, \quad (6.27)$$

$$DSL S_i(\underline{x}) = 1 - H(SF_{\delta LL,s,i}(\underline{x})), \quad (6.28)$$

$$LS_{slab}(\underline{x}) = 1 - [H(SF_{M+,c}(\underline{x})) + H(SF_{M-,c}(\underline{x})) + H(SF_{Q,c}(\underline{x})) + H(SF_{\delta SW,c}(\underline{x})) + H(SF_{M+,s}(\underline{x})) + H(SF_{M-,s}(\underline{x})) + H(SF_{Q,s}(\underline{x})) + H(SF_{\delta LL,s}(\underline{x}))]/8, \quad (6.29)$$

$$VSLS(SF(\underline{x})) = \begin{cases} 1 - H(SF_{Rmax,s}(\underline{x})) \\ 1 - H(SF_{Rres,s}(\underline{x})) \end{cases}. \quad (6.30)$$

These functions provide a value greater than zero if not all the LSs involving them are fulfilled, and equal to zero if all the LSs are met. The function  $VSLS(\underline{x})$  has two possible definitions depending on whether the impulsive acceleration wants to be limited.

#### 6.5.4 Optimization algorithm

The evolutionary optimization algorithm 'Non-Dominated Sorting Genetic Algorithm II', best known as NSGA-II, for constrained and discrete multi-objective optimization, has been used in this study. The algorithm version used is available in the Python library 'pymoo' and has been implemented according to [201]. A random sampling of integer values has been performed to generate the initial solutions. A constraint handling method based on the principle 'Feasibility First' has been used to avoid the definition of any penalty function. This methodology was proposed by Deb *et al.* [202] and uses a fitness function (applied to each solution) that depends on the current population. When tournament selection is applied to these fitness values, feasible solutions are always emphasized over infeasible ones. A simulated binary crossover based on [202] with a crossover index  $\eta_c = 3$ , and a probability of crossover for each variable of  $p_c = 0.5$ , has been used. A polynomial mutation has been employed with a mutation parameter  $\eta_m = 3$  and a probability of mutation  $p_m = 0.5$ . The histograms used for crossover and mutation have been rounded to deal with integer variables. Finally, for each optimization performed 100 generations with a population of 100, have been used.

## 6.6 Parametric study

The optimization problem proposed has been used to develop a parametric study in which many different floor bays are optimized with and without CLD. This has been built by combining four different parameters which are needed to optimize a given floor bay:

- $L_i$ : The length of the 1<sup>st</sup> and 2<sup>nd</sup> beams of the floor. The parametric study has been focused on analyzing square floor bays, where  $L_1 = L_2$ .  $L_i$  has been varied from 4.5 m to 19.5 m each 1.5 m, analyzing a whole set of 11 possibilities for this parameter.
- $R_{lim}$ : The limiting response factor of the floor bay to define the VSLS. Four different possibilities have been considered for  $R_{lim}$ . First, a  $R_{lim} = \infty$ , which corresponds to floor designs in which the VSLS has not been checked, here denoted as 'Statically designed floors'.  $R_{lim} = 8$ , which is the limitation used for regular electronic offices.  $R_{lim} = 4$  is the limit used for quiet spaces like silent offices or libraries. Finally,  $R_{lim} = 2$  would apply to hospital floors.
- $SF_{VSLS}$ : The  $SF$  used to define the VSLS. Two possibilities are contemplated,  $SF_{Rmax}$  which limits the impulsive and resonant floor responses, and  $SF_{Rres}$  which only limits the resonant response.
- $CLD_{int}$ : This indicates if the CLD treatment has been integrated into the design. Two possibilities are studied,  $CLD_{int} = CLD$  and  $CLD_{int} = NO CLD$ .

The following vectors provide a summary of the four parameters used and the values they can adopt:

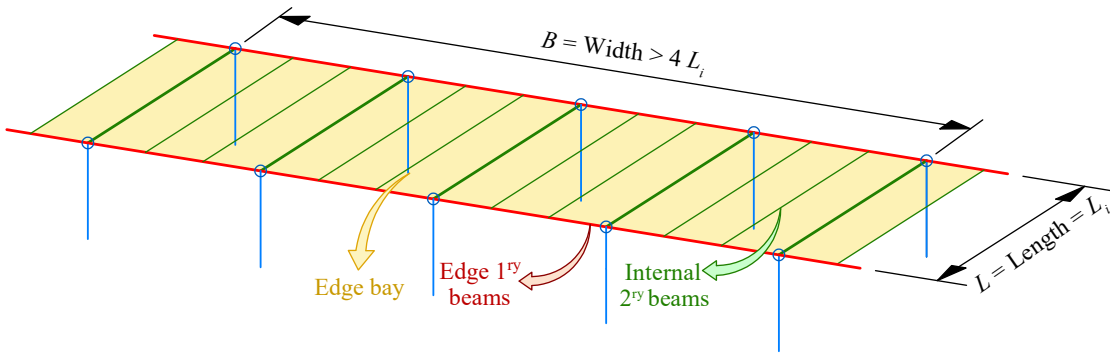
$$\begin{aligned}
 L_i &= [4.5, 6.0, 7.5, 9.0, 10.5, 12.0, 13.5, 15.0, 16.5, 18.0, 19.5], \\
 R_{lim} &= [2, 4, 8, \infty], \\
 SF_{VSLS} &= [SF_{Rmax}, SF_{Rres}], \\
 CLD_{int} &= [NO CLD, CLD].
 \end{aligned} \tag{6.31}$$

A total of 176 cases (resulting from combining all the different possibilities  $11 \times 4 \times 2 \times 2 = 176$ ) have been analyzed. One particular case can be, for example, the one defined by the vector  $[9, 4, SF_{Rmax}, NO CLD]$ , which corresponds to a 9 m  $\times$  9 m floor

bay, designed to comply with a maximum response factor of 4, including the impulsive and resonant responses, and without any integrated CLD treatment.

For each optimized floor bay seven design parameters result from the optimization problem if the CLD is integrated:  $h_c$ ,  $R_d$ ,  $P_1$ ,  $P_2$ ,  $\lambda_1$ ,  $\lambda_2$  and  $(N_2 - 1)$ . If the CLD is not used, this number reduces to five as  $\lambda_1$  and  $\lambda_2$  are set to 0.

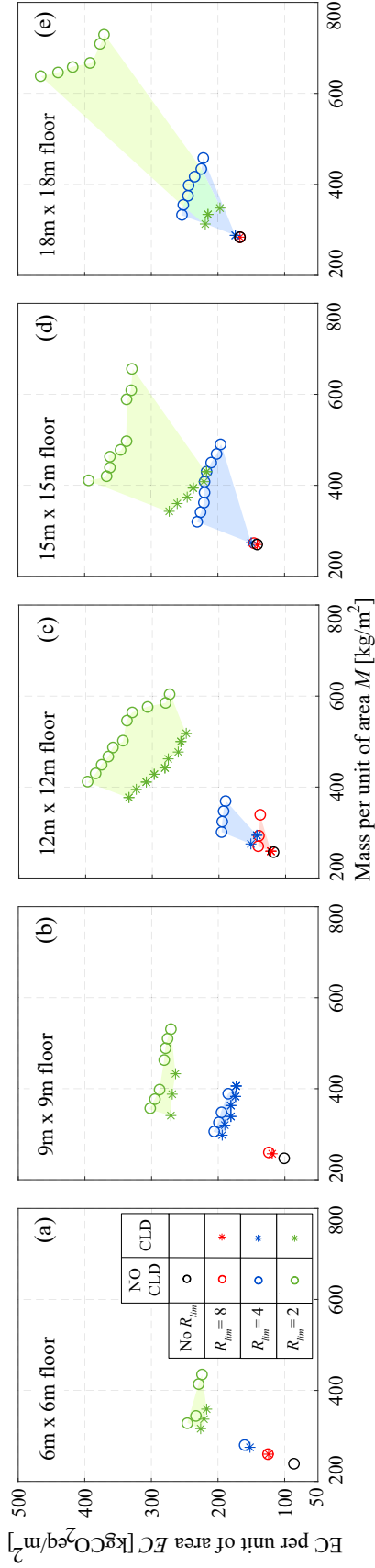
The geometry configuration of the whole floor to which the floor bays optimized belong is a row of bays sharing a secondary beam between them, as depicted in Figure 6.6.



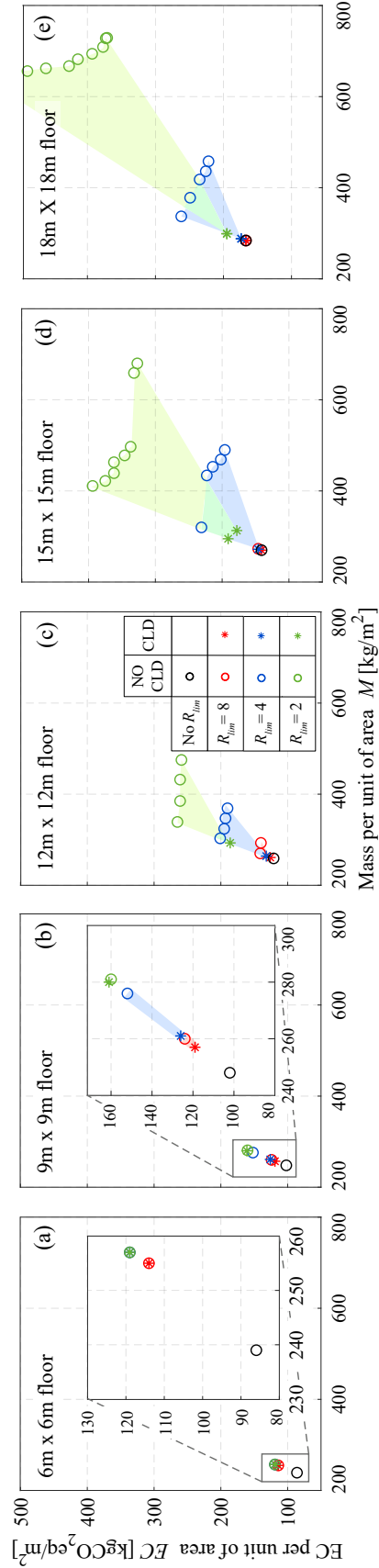
**Figure 6.6:** Floor configuration composed of edge bays used for the parametric study.

### 6.6.1 Results

For each case, a multi-objective optimization has been performed. Figures 6.7 and 6.8 provide the Pareto fronts of the achieved global optima for different floor spans, different vibration limitations and, with and without CLD treatment. The first one has been obtained using  $SF_{Rmax}$  and the second one making use of  $SF_{Rres}$ . Shaded areas in green, blue, and red represent the difference in the Pareto space between the optimal designs obtained without and with CLD. The bigger these areas, the higher the effectiveness of the CLD treatment.

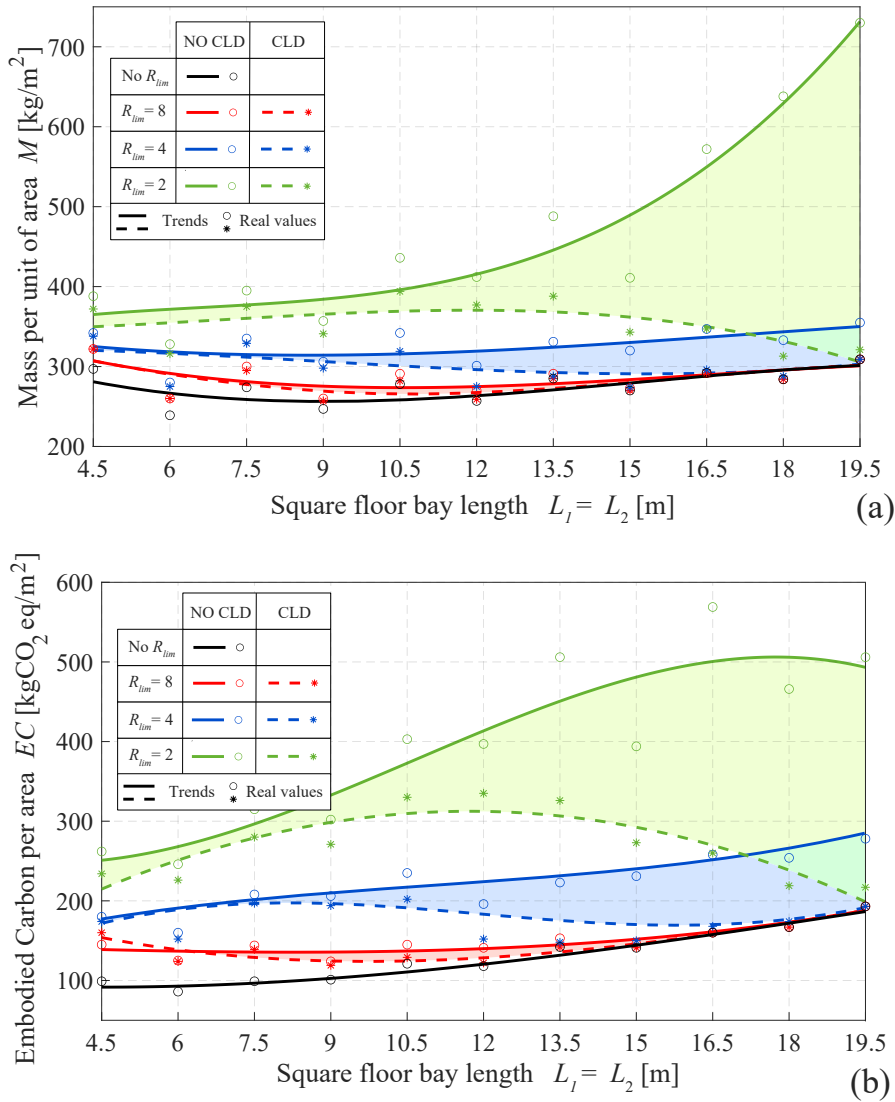


**Figure 6.7:** Pareto fronts of the floors in terms of  $M$  and  $EC$  designed with  $SF_{R_{res}}$  and for different spans: (a) 6 m, (b) 9 m, (c) 12 m, (d) 15 m (e) 18 m.

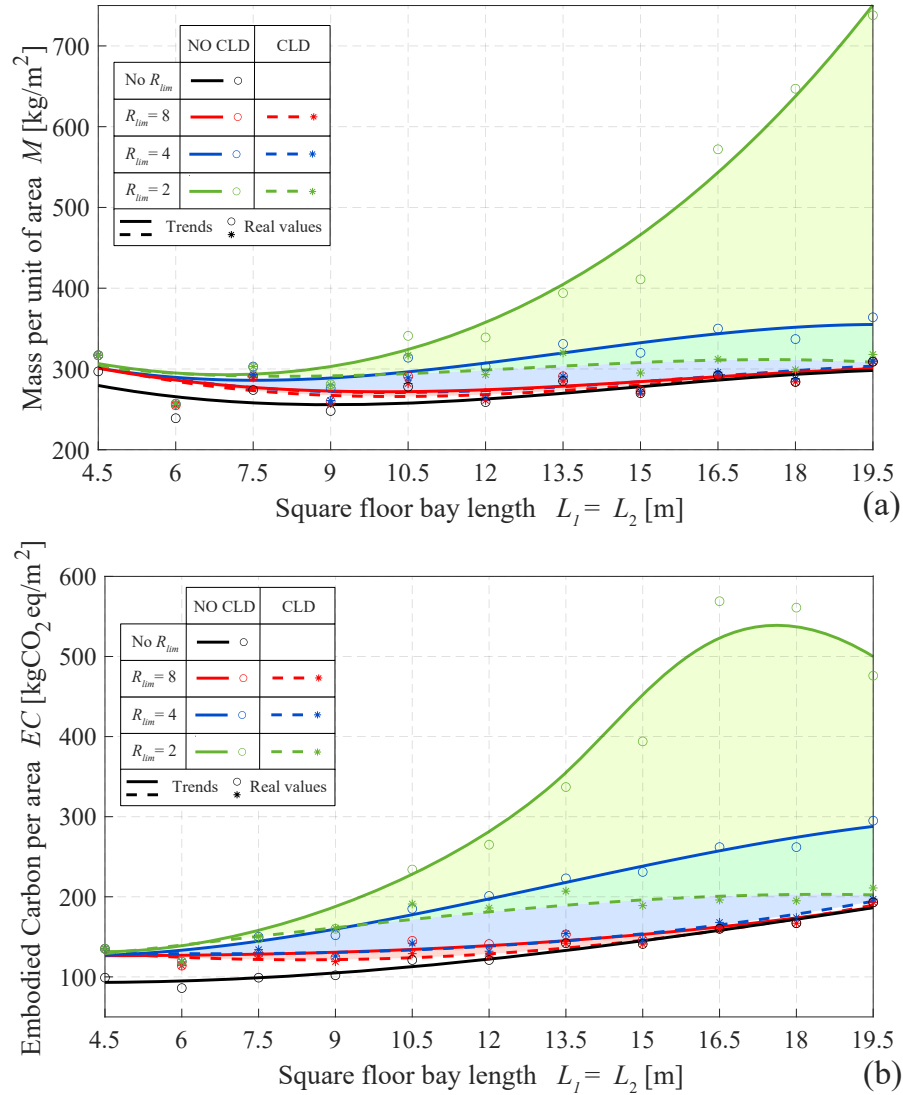


**Figure 6.8:** Pareto fronts of the floors in terms of  $M$  and  $EC$  designed with  $SF_{R_{max}}$  and for different spans: (a) 6 m, (b) 9 m, (c) 12 m, (d) 15 m (e) 18 m.

For each studied case, the lightest designs (those with an optimal mass  $M$  and located at the left edge of each Pareto front) have been represented in terms of their  $M$  and  $EC$  depending on the span. Figures 6.9 and 6.10 correspond to floors designed using  $SF_{Rmax}$  and  $SF_{Rres}$ , respectively. Polynomial trend curves have been included in these charts for a better interpretation of the results. The shaded areas in these figures have the same function as in the previous ones.



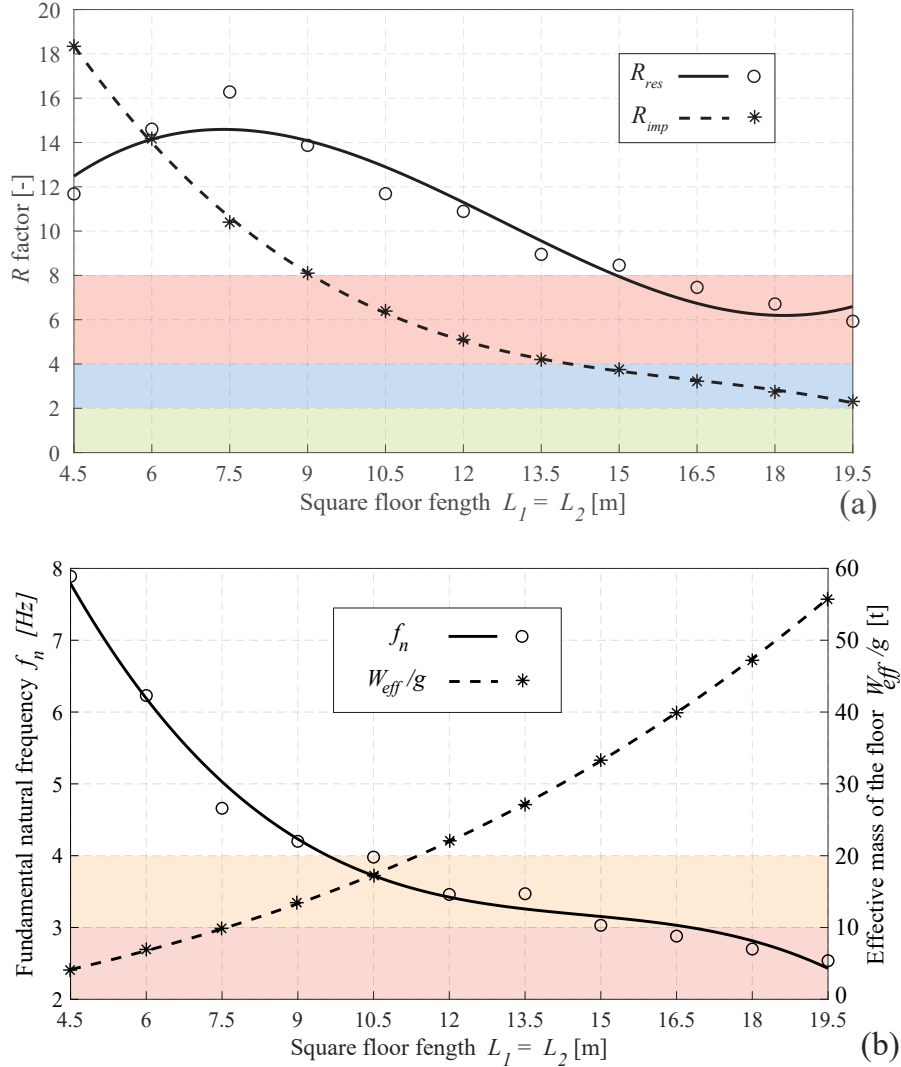
**Figure 6.9:** Floors designed with  $SF_{Rmax}$ , optimal designs in terms of mass per square meter. (a) Mass per square meter  $M$ . (b) Embodied carbon per square meter  $EC$ .



**Figure 6.10:** Floors designed with  $SF_{R_{res}}$ , optimal designs in terms of mass per square meter. (a) Mass per square meter  $M$ . (b) Embodied carbon per square meter  $EC$ .

Finally, within the previous figures, the black circles and lines represent the static designs in which the VSLs has not been checked. When imposing a more restrictive vibration limitation, these floor designs must be changed in terms of mass, stiffness, or damping to meet the new VSLs. To provide a meaningful interpretation of these, the  $R_{res}$  and the  $R_{imp}$  of these statically designed floors have been represented together with their  $f_n$  and  $W_{eff}/g$  in Figure 8.2.(a)-(b), respectively. Shaded areas in Figure 8.2.(a) represent the vibration limitation used in the parametric study. Shaded areas in Figure 8.2.(b) represent the frequency restriction of 3 or 4 Hz that some design codes impose on

long-span floors to avoid excessive low-frequency vibrations.



**Figure 6.11:** Statically designed floors without CLD and with  $R_{lim} = \infty$ . (a) Dynamic response of the floors in terms of  $R_{res}$  and  $R_{imp}$ . (b) Dynamic parameters of the floors  $f_n$  and  $W_{eff}$ .

### 6.6.2 Discussion

The first finding to note in Figures 6.7–6.10 is that the statically designed floors are the ones with less  $M$  and  $EC$ . Also, the Pareto front in these cases converges to one point, as the concrete slab is kept as light as possible.

It is also clear from the results obtained that the more restrictive the vibration limitation, the higher the oversizing of the floor to meet the VSLS.

In floors designed without CLD, when imposing more restrictive  $R_{lim}$  values (especially 4 and 2), the Pareto front begins to open. This widening effect is more evident in two cases:

- In long-span floors with span  $> 12$  m (as can be seen in Figures 6.7d,e and 6.8.(d)-(e)). This can be explained by observing in Figure 8.2.(a),(b) that long-span floors have a dynamic response dominated by  $R_{res}$ . They also have low values of  $f_n$ . On the one hand, the excessive resonant vibration may be tackled by stiffening the steel profiles of the floor (which implies a high  $EC$  cost, but has a low repercussion in  $M$ ) to increase its  $f_n$  and thus, reduce the amplitude of the exciting human harmonic  $\alpha_h$ . On the other hand, a solution with less  $EC$  cost but more impact on the final floor's  $M$ , is to thicken the concrete slab to reduce the floor resonant response. These two possibilities are the extreme solutions of the Pareto fronts.
- In short-span floors designed using  $SF_{Rmax}$  (compare, for example, Figure 6.7.(a),(b) with respect to Figure 6.8.(a),(b)). Again, looking at Figure 8.2.(a),(b), it is noticeable that short-span floors have higher values of  $R_{res}$  and  $R_{imp}$ , higher values of  $f_n$ , and lower values of  $W_{eff}$ . In these floors,  $R_{res}$  can be optimally reduced with a minimum stiffening of the floor that effectively rises  $f_n$  the right amount to meet the VSLS (this explains why in Figure 6.8(a),(b), the Pareto front converges to 1 point). Nevertheless, reducing the floors'  $R_{imp}$  requires, either a major stiffening of the floor, (which reduces the value of the effective impulse loading  $I_{eff}$ ) or a substantial increase of its  $W_{eff}$  (to reduce the impulsive response). Hence, controlling the impulsive vibration  $R_{imp}$  produces a significant oversizing of short-span floors compared to when it is not controlled (see results of Figures 6.9 and 6.10 for span values lower than 12 m).

Regarding the effectiveness of the CLD integration in the final design of the floor, the following conclusions may be extracted:

- The CLD integration enables increasing the damping ratio of the floor  $\xi_n$ . Hence, it is mainly effective when implemented in floors in which the resonant response  $R_{res}$  is the dominant one, i.e., long-span floors with values of  $R_{lim}$  around 4 or 2. This can be appreciated in Figures 6.7.(d),(e) and 6.8(d),(e), and also a bit in Figures 6.7.(c) and

6.8.(c). Table 6.5 provides 15 m and 18 m floors, the percentage of oversizing with respect to the statically designed cases (those not meeting the VSLs), for solutions located at the middle of the Pareto front. When CLD is not used, this oversizing in terms of  $M$  and  $EC$  is around 100% for floors with  $R_{lim} = 2$ , and around 50% for floors with  $R_{lim} = 4$ . When the CLD is used the oversizing decreases to around 20% for the  $M$ , and an average value of 34% for the  $EC$ , in floors with  $R_{lim} = 2$ . When  $R_{lim} = 4$  the oversizing decreases to 2% for the  $M$ , and 5% for the  $EC$ . This decrease is even more evident when checking the VSLs using  $SF_{Rres}$ .

- The CLD does not result as effective in short-span floors (those with a span  $\leq 10$  m). On the one hand, When assessing the VSLs according to  $SF_{Rmax}$ , a substantial big increase of  $\xi_n$  does not have a significant impact on reducing the impulsive response of the floor. On the other hand, when using  $SF_{Rres}$ , the resonant response of these floors seems to be better tackled by minimally stiffening the floors rather than increasing their damping. Both conclusions are clear when looking at Figures 6.9 and 6.10 for spans lower than 10 m.

**Table 6.5** Oversizing in terms of  $M$  and  $EC$  of floor designs with 15 m and 18 m span, that meet different VSLs, with respect to the statically designed floors ( $R_{lim} = \infty$ ).

VSLs Type	$L_i[m]$	CLD Treatment	$M$ Oversizing [%]	$EC$ Oversizing [%]
$SF_{Rmax} - R_{lim} = 2$	15	NO CLD	84	139
		CLD	45	70
	18	NO CLD	134	134
		CLD	18	28
$SF_{Rres} - R_{lim} = 2$	15	NO CLD	84	139
		CLD	9	35
	18	NO CLD	134	155
		CLD	5	16
$SF_{Rmax} - R_{lim} = 4$	15	NO CLD	51	56
		CLD	2	7
	18	NO CLD	40	46
		CLD	2	5
$SF_{Rres} - R_{lim} = 4$	15	NO CLD	60	58
		CLD	1	4
	18	NO CLD	40	43
		CLD	2	4

- Floors with a span of around 12 m represent a transition zone between short-span and long-span floors. In this intermediate range of spans the CLD efficacy is perceptible but not as high as on long-span floors.
- For floor designs in which  $M$  is the minimum possible, (as those depicted in Figures 6.9 and 6.10) the CLD effect can be summarized as follows: for floors with a  $R_{lim} = 4$ , the CLD enables a reduction by around 50 kg/m<sup>2</sup> and 100 kgCO<sub>2</sub>eq/m<sup>2</sup> with respect to the cases when it is not used. In floors with  $R_{lim} = 2$ , this reduction increases with the span, with an average of 200 kg/m<sup>2</sup> and 250 kgCO<sub>2</sub>eq/m<sup>2</sup>.

## 6.7 Conclusions

This Chapter shows the integration of CLD treatments into the design workflow of composite floors prone to vibrate. This treatment consists of a thin VE layer included between the steel member and the concrete slab of composite floor beams for a proportion of their length near the supports. This technology enables increasing the floor-damping ratio when vibrating in vertical bending modes, which allows for the reduction in the amount of additional mass or stiffness typically increased to overcome the VSLs

A constrained discrete multi-objective optimization problem has been proposed to design a floor bay with different CLD treatments applied on their 1<sup>st</sup> and 2<sup>nd</sup> beams. Seven design variables of the floor have been considered. The design constraints of the problem are the different LSs of the floor, and two OFs have been used: the embodied carbon and the mass of the floor per unit of area.

Finally, a parametric study for different square floor bays, with spans varying from 4.5 to 19.5 m, has been carried out to compare the optimal structural solutions obtained with and without making use of the CLD treatment. Four different limits of vibration have been imposed from less to more restrictive. The results obtained indicate that for long-span floors (>12 m) the reduction in terms of mass and EC is substantial. The CLD enables the reduction in the structural oversizing in terms of mass from values of 100% or 50% to around 20% or 2% for floors meeting a VSLs limited by response factors of 2 or 4, respectively. Moreover, when the impulsive vibration of the floor is not checked, this enhancement is even higher.

Future works will be focused on studying the efficacy of this CLD treatment when implemented on lightweight timber floors.



# 7

## Conclusions

This doctoral thesis has studied a new approach of designing composite lightweight floors prone to excessively vibrate under human-induced excitations. This consists of integrating a VE CLD treatment between the concrete slab and the steel profile of the composite beams in order to significantly increase their fundamental damping ratio. The thesis has been focused on four main points: i) understanding the modeling of these treatments, ii) developing an accurate methodology for designing them, based on a simplified FE model and on the use of real modal analysis, useful for current engineering practice at the design stage, iii) experimentally validating the models studied, through carrying out tests on reduced-scale models, and iv) the development of a whole framework for the optimal design of composite floors with integrated CLD treatments.

Some general conclusions of the thesis are outlined below:

- First, from a deep review of the literature related to the research field of floor vibrations, developed in Chapter 2, it is clear that floor vibrations have become an increasing concern for the building engineering community. Hence, the first conclusion extracted in this thesis is that the impact of the technology researched may be remarkable for the development of floors.
- As shown in Chapter 3, for the first time, an analytical exact solution has been derived for partially CLD-treated beams. The parametric study may be useful for easy and fast checks on the additional damping ratio provided by a given treatment

to the different vibration modes of a composite beam. Additionally, a novel iterative procedure to solve the partially-treated sandwich beams has been proposed and used.

- In Chapter 4, a deep comparison between analytical and numerical modelling approaches has been performed, illustrating a strong alignment in results for fully treated beams, but revealing a notable disparity in outcomes when modelling partially treated beams. This divergence is likely attributed to the chosen approach in modelling slabs through analytical equations.
- A simple and aware FE modelling approach has been proposed. This is based on representing the VE layer with spring elements, and on the use of real modal analysis in combination with a modified MSE method. The methodology has been validated against more precise ones and against experimental tests. The proposed modelling approach is suitable for its use in floor designs in daily engineering practice. Additionally, due to its simplicity, it is suitable to be used with reliability analyses.
- In Chapter 5, the effectiveness of CLD treatments has been validated experimentally, through testing reduced-scale composite beams. For this purpose, a design methodology of reduced-scale specimens has been proposed and used. It has been demonstrated the linearity of the mechanical behaviour of CLD-treated beams no matter the amplitude of the dynamic excitation. Additionally, certain deviations have been detected when predicting the damping ratio for the same specimen, but with different methodologies. Finally, temperature has been demonstrated to be a key parameter in the dynamic performance of these treatments.
- In Chapter 6, an important contribution has been made concerning the structural optimization of composite floors considering their VSLs performance. The impact of the VSLs on the final sizing of a set of composite floor designs has been assessed, proving that it might be especially influential.
- Interesting relationships have been unveiled between the use of more mass or stiffness depending on the variable to be optimized on the floor when applying traditional design approaches against vibration. On the one hand, increasing the mass of the floor through thickening the concrete slab seems to be a better solution if the EC wants to be minimized. On the other hand, if the floor's weight wants to be minimized, a stiffening approach based on increasing the steel profiles is recommended.
- Finally, it has been demonstrated that the integration of CLD treatments may provide more sustainable and lightweight floors when the VSLs requirements to

comply are restrictive. The CLD treatment has been proven to be a more convenient solution when response factors want to be reduced values of 8 to 4 or even 2.

### 7.0.1 Scientific Contributions derived from the thesis

The following scientific contributions have been directly derived from this thesis:

#### Indexed research papers

- C. M. Renedo, I. M. Díaz, and J. H. García Palacios, “Modelling of thin constrained layer damping treatment applied to composite floor beams,” *Structures*, vol. 56, p. 105 032, Oct. 2023, issn: 23520124. doi: 10.1016/j.istruc.2023.105032. [203]
- C. M. C. Renedo, I. M. Díaz, J. H. García-Palacios, and C. Gallegos-Calderón, “Structural optimization of lightweight composite floors with integrated constrained layer damping for vibration control,” *Actuators*, vol. 12, p. 288, 7 Jul. 2023, issn: 2076-0825. doi: 10.3390/act12070288. [204]

#### Conference papers

- C. M. C. Renedo, I. M. Díaz, J. M. Soria, and J. H. García-Palacios, “Designing a footbridge with an integrated TMD: Improvement assessment,” *Proceedings of the CNM 2019*, Jul. 2019, pp. 688–703, ISBN: 978-989-54496-0-6. [205]
- C. M. C. Renedo, I. M. Díaz, and J. H. García-Palacios, “High-performance dynamically-loaded structures: Integrating smart dampers,” *Proceedings of the International fib Symposium of Conceptual design of structures*, Sep. 2019, pp. 33–41, ISBN: 978-2-940643-02-8. [206]
- C. M. C. Renedo, I. M. Díaz, J. H. García-Palacios, and S.Zivanovic, “Modelling of highly-damped composite floor beams with constrained elastomer layers,” *Proceedings of the CMMoST 2019*, Oct. 2019, pp. 507 521, ISBN: 978-84-17924-58-4. [207]
- C. M. C. Renedo, W. P. Ortega, I. M. Díaz, and J. H. García-Palacios, “Composite floor beams with constrained layer damping: Experimental tests on reduced scale models,” *Proceedings of the DINEST 2021*, Universidad de Oviedo, Jul. 2021, pp. 159–168. [156]

- P. V. Fernández, C. M. C. Renedo, I. M. Díaz, and J. H. García-Palacios, “Structural optimization of lively composite floors with integrated constrained layer damping,” Proceedings of the CMMoST 2021, Dec. 2021, pp. 474–487, ISBN: 978-84-09-39323-7. [208]

# 8

## Ongoing and future research

The work started in the present doctoral thesis is planned to be continued over the next few years. The author aims to develop an enriched investigation about the integration of different damping technologies on the design of structures susceptible to excessively vibrating in serviceability conditions.




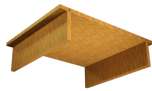


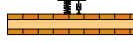
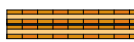
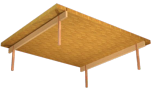

















The author plans to deliver two research papers derived from this thesis:

- A research paper based on the sectional solution of the PDE of the VE-core sandwich beam, which has been studied in detail in Chapter 3 of this document.
- A research paper based on the experimental works shown in Chapter 5 of this thesis.

Currently, the author is working on two investigations that directly continue with the works started in this thesis. these works are the following ones:

- During his research exchange period at the University of Bath, the author of this thesis started to research the integration of vibration mitigation solutions within the design of timber floors built from EWPs. This research aims to study and compare in terms of mass, EC and price 3 types of solutions, namely: i) the use of concrete toppings ii) TMDs, and iii) the CLD treatment studied in this thesis. The applicability of this solutions will be applied to 3 types of timber floors made with

CLT slabs and glue-laminated beams. The study aims to explore the competitiveness of damping technologies against alternatives based on adding mass to the floor as the concrete topping. A summarizing table with the number of cases studied is here provided:

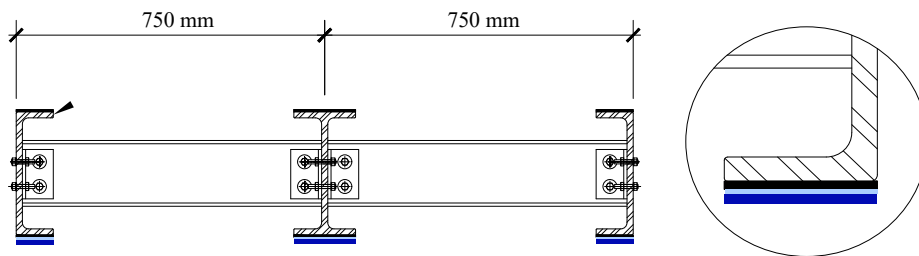
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**Figure 8.1:** Comparison of Different VMSs to different types of timber floors made of CLT and glue-laminated beams

- A second investigation in which the author is involved consists on employing the CLD treatment studied in this thesis as a retrofitting solution. This means, to use it as a remedial solution to increase the damping ratio of an already existing structure. The chosen structure is the full-FRP footbridge present in the laboratory of structures of ETSI Caminos, Canales y Puertos of the Universidad Politécnica de Madrid. This footbridge was initially design by the Structural Engineering Group (the one to which the author belongs) as a lively structure that would fulfil all design requirements except for vibration. In this case, a layer of carbon fibre reinforced polymer will be used to constrain a VE layer included under the lower flange of the footbridge.

Finally, the following topics are proposed as future research lines that could be directly addressed after the works shown in this thesis:

- The development of a real application example of a CLD treatment to a full-scale instrumented floor in which being able to measure the actual deformation capacity of the VE treatment under the real BCs of the floor.



**Figure 8.2:** Application of a retrofitting VE treatment to the lively footbridge of the laboratory of structures of ETSI Caminos, Canales y Puertos

- The development of an energetic equilibrium carried out experimentally to realistically assess how much of the dissipated energy is actually being gone within the VE layer.
- The extension of this integrated-damping design approach to the case of footbridges by means of using TMDs as a damping solution. Currently, at least in Spain, structural designers tend to oversize a lot the stiffness of footbridges so they do not suffer from excessive vertical or lateral vibrations. In fact, the Spanish code enables to avoid a vibration analysis if the deflection of the footbridge under the frequent live load is lower than  $L/1200$ . TMDs are an economical, easy-to design and robust option that will enable to design lighter footbridges with better dynamic performance.
- To explore the implementation of this CLD treatment in timber floors based on CLT slabs supported by glue-laminated beams. many questions arise in this case. ¿would it be is necessary to implement and adhesive in this cases?, ¿Is sufficiently rigid the

CLT slab so the treatments ends being effective?.

- To perform a delicate analysis of the CLD treatment modelling in full-scale floors be means of a detailed FE models.

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