Sustainability of Column-Supported RC Slabs: Fiber Reinforcement as an Alternative

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Abstract: Fiber-reinforced concrete has been used in structures without any additional reinforcement when the design is determined by transient load stages (precast segments for tunnels), in elements with favorable boundary conditions, and in structures subjected to low load levels (pavements or pipes). Recently, the material has been used as the primary reinforcement in elements with greater structural responsibility, such as building column-supported slabs. Several dozen buildings have incorporated this new technology, and research is being conducted on how to optimize the design while guaranteeing the required reliability levels. However, in some cases, fibers have not been used as the primary reinforcement in concrete slabs for economic reasons. In most cases, the solution is compared with existing alternatives (traditionally reinforced concrete) considering only the direct material costs and disregarding indirect costs, social aspects, and environmental factors. The building construction sector lacks sustainability rating tools to assess structural components separately (e.g., columns, floors, panels, and façades). This paper presents a new method that can be used to assess the sustainability of concrete slabs by means of a multicriteria decision-making approach including fiber-reinforced concrete. It used rigorous analyses of current concrete slab technologies and sustainability assessment tools. Criteria, indicators, weights, and value functions were specifically selected, defined, and calibrated for this research. **DOI: 10.1061/(ASCE)CO.1943-7862.0001667.** *© 2019 American Society of Civil Engineers.*

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Introduction

Buildings can play an important role in improving the sustainability of society through the reduction of their economic, environmental, and social impacts (European Commission 2016). Of the various parts of a building, this paper focuses on floors, which can be defined as the horizontal parts of the building structure that directly receive loads to be transmitted to other structural elements (Calavera 2003).

Floors can be built using different components, materials, construction processes, and structural schemas. The most frequently used component today is slabs, which can be made of wood (AWC 2015), composite (SDI 2017), or RC (Kind-Barkauskas et al. 2002). Likewise, in terms of the construction process, floors can be built on site (Kind-Barkauskas et al. 2002), partially industrialized (AWC 2015), or completely prefabricated. Finally, with regard to structural typology, slabs can be unidirectional, bidirectional, or multidirectional, and solid or hollow-core (AWC 2015).

More recently, fiber-reinforced concrete (FRC) has emerged as an alternative cement-based material for structural applications. Several technical advantages of using steel fiber–reinforced concrete (SFRC), in particular, have been reported, including cracking control, ductility, and impact resistance enhancement, among others. Additionally, because fibers are added directly at the concrete plant, on-site labor and time needs decrease significantly. In this regard, where required, concrete steel-bar reinforcement operations (handling and placing) can be minimized in order to optimize execution time. Occupational safety is thus also improved due to the minimization of risks associated with the handling of traditional reinforcement.

FRC technology has advanced significantly, primarily due to its acceptance in the *fib Model Code 2010* (MC-2010) (*fib* 2013). This has boosted its use in several fields: ground-supported slabs (Meda et al. 2004), sewerage pipes (de la Fuente et al. 2012a, 2013), reinforced earth-retaining walls (de la Fuente et al. 2011), tunnel linings (Chiaia et al. 2009; de la Fuente et al. 2012b; Liao et al. 2015a, b; Meda and Rinaldi 2014), and others (e.g., wind turbine supports, water storage tanks, and retrofit and repair applications).

Additionally, SFRC has been successfully used in flat slabs in real buildings (Table 1) and its structural behavior has been extensively researched by means of full-scale tests (Blanco et al. 2015a, b; Destrée and Mandl 2008; Ellouze et al. 2010; Gossla 2005; Hedebratt and Silfwerbrand 2014; Maturana 2013; Michels et al. 2012; Pujadas et al. 2012, 2014; Salehian and Barros 2015), numerical simulations (Blanco et al. 2015a; Gödde and Mark 2015), and the examination of design aspects (Destrée 2004; Destrée and Mandl 2008; Maturana et al. 2014; Maturana et al. 2010). In these experiences, span lengths up to 8.00 m have been achieved using steel macrofibers in amounts between 40 and 100 kg/m^3 to withstand the typical service loads expected in residential and offices building. It is recommended that self-compacting concrete be used to eliminate vibrating operations and speed construction. Concrete compressive strengths ranging from 30 to 60 N/mm^2 are used.

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Table 1. Experimental research programs of steel fiber–reinforced concrete flat slabs and real buildings constructed using this technology

Author	Type	Country	Maximum span (m)	Rebars	C_f (kg/m^3)	λ_f/l_f-type
Falkner (2007) and Hedebratt and Silfwerbrand (2014)	FSLT	Germany	5.00 · 5.00 · 0.15	Yes	40	80/60-HE
Hedebratt and Silfwerbrand (2014) and Døssland (2008)	FSFT	Norway	3.00 · 7.00 · 0.15	None/yes	62	65/60-HE
Hedebratt and Silfwerbrand (2014), Gossla (2005), and Destrée and Mandl (2008)		Luxembourg	6.00 · 6.00 · 0.20	Yes	100	39/50-C
Destrée and Mandl (2008)		Estonia	5.00 · 5.00 · 0.18		100	
Destrée and Mandl (2008)		Belgium	3.10 · 3.10 · 0.16	None	45	54/35-TCE
		Australia			45	
Hedebratt and Silfwerbrand (2014), and Destrée and Mandl (2008)	RB	Latvia	6.00 · 6.00 · 0.25	Yes	100	39/50-C
		Estonia	—			
Hedebratt and Silfwerbrand (2014), and Öšlejs (2008)		Latvia	4.00 · 4.00 · 0.16	—		
Maturana (2013)		Spain	8.00 · 7.60 · 0.30	Yes		
Michels et al. (2012)	SST	Switzerland	2.34Φ0.20	None		
Hedebratt and Silfwerbrand (2014)	FSFT	Sweden	3.00 · 3.00 · 0.13	Yes	40-80	65/60-HE
Salehian and Barros (2015)	SST	Portugal	1.20 · 1.00 · 0.075		90	74/37-HE

Note: FSFT = full-scale field test; FSLT = full-scale lab test; RB = real building; SST = small-scale test; HE = hooked-end; C = crimped; TCE = twin-cone ends; C_f = amount of structural fibers (steel); l_f = length of the fiber; and λ_f = aspect ratio of the fiber (length/diameter of the fiber).

Furthermore, there is already a technical recommendation, ACI 544.6R (ACI 2015), specifically oriented toward facilitating the design of SFRC pile-supported flat slabs.

Although both the experimental programs and several experiences in real buildings have confirmed the technical and economic appeal of this technology in a wide range of spans and service loads, its use is not yet established, because only some of the benefits have been reported. In fact, in most cases the decision of whether to use steel fibers (SFs) or traditional reinforcement is made based on the direct material costs, disregarding overall costs, social aspects, and environmental factors. Floors account for 10%–20% of the material and execution costs of a building, surpassed only by the cost of services and façades (Pons 2009; Regalado 1999). Their environmental impact varies depending on their structural complexity (John et al. 2009).

With regard to sustainability performance assessment, several methods and tools make it possible to take into account the three main pillars of sustainability; for instance, generic rating tools such as the Building Research Establishment Environmental Assessment Method (BREEAM 2016), the German Sustainable Building Council System (Deutsche Gesellschaft für Nachhaltiges Bauen) (DGNB 2018), Leadership in Energy and Environmental Design (LEED) (USGBC n.d., 2015), VERDE (Macías and García Navarro 2010), and the models in Pons and Aguado (2012) and Casanovas-Rubio and Armengou (2018). Nevertheless, although these tools can provide a global sustainability index (or grade) for buildings or structural systems, they are not meant to assess specific structural parts (e.g., foundations, columns, and floors), and thus do not provide reliable and objective results for comparing different concrete reinforcement alternatives for use in building floors. Some methods have been defined to evaluate specific structural parts such as structural concrete columns (Pons and de la Fuente 2013), vertical additions for improving the energetic behavior of masonry buildings (Terracciano et al. 2015), or for the selection of sustainable materials for building projects (Akadiri et al. 2013). However, the literature review did not reveal a specific method to evaluate the sustainability of building slabs.

Therefore, this paper proposes a method for assessing the sustainability of reinforced concrete slabs using the Integrated Value Model for Sustainability Assessment (MIVES) (Aguado et al. 2012; Alarcon et al. 2011; Villegas et al. 2010). This method makes it possible to make decisions regarding the most suitable reinforcement strategy for any type of floor for building construction by considering the sustainability pillars as well as stakeholder satisfaction. Special attention was paid to occupational safety issues in construction and the assessment thereof. To this end, a novel multicriteria risk assessment method (Casanovas et al. 2014) was coupled with MIVES in order to objectively consider the different occupational risks entailed in each of the analyzed column-supported slab construction methods.

As a case study and example of application, the method proposed here was used to assess the sustainability performance of two different reinforcement solutions for the concrete flat slabs of the LKS Spanish headquarters building in Spain (Maturana 2013). The slabs for this office building were originally designed as an RC solution; however, ultimately, self-compacting steel fiber–reinforced concrete was used due to various advantages (overall cost and construction time), without considering other environmental and social aspects that are also enhanced by this innovative solution.

Sustainability Assessment of Building Flat Slabs Based on MIVES

Background of MIVES

MIVES is a multicriteria decision-making (MCDM) approach that enables the sustainability assessment of processes and products minimizing the subjectivity associated with the indicators involved. To this end, it considers value functions (Aguado et al. 2012; Alarcon et al. 2011; Villegas et al. 2010) and an analytic hierarchy process (AHP) (Saaty 1990). Additionally, statistical methods have been developed to properly account for the inherent uncertainties in order to maximize both the robustness and reliability of the results (del Caño et al. 2012, 2016). Among other possible methods, MIVES was chosen because it has been defined to assess sustainability and can be adapted to specific structural building components.

The MIVES method has already been used as an MCDM method in various heterogeneous fields: buildings and components (Pons and Aguado 2012; Pons and de la Fuente 2013; Reyes et al. 2014; San-Jose and Cuadrado 2010; San-Jose and Garrucho 2010), tunnel infrastructure (de la Fuente et al. 2017b; Ormazabal et al. 2008), hydraulic structures (de la Fuente et al. 2016; Pardo and Aguado 2014), electricity generation systems and infrastructure

(Cartelle et al. 2015; de la Fuente et al. 2017a), and even post-disaster housing management (Hosseini et al. 2015, 2016). MIVES is also included in the current Spanish Structural Concrete Code (CPH 2008) for assessing the sustainability of concrete structures (Aguado et al. 2012).

General Aspects of MIVES Approach

This approach requires defining three fundamental aspects: (1) the system boundaries that determine the scope of the analysis; (2) the requirement tree to encompass the requirements (R), criteria (C), and indicators (I) involved in the decision-making process; and (3) the value functions that convert the attributes or physical units associated with each indicator into one-dimensional values from 0 to 1. The AHP method is used to assign weights to the requirements, criteria, and indicators.

Seminars were organized to define the requirement tree and its criteria, indicators, weights, and value functions. The seminars consisted of nine experts, civil and industrial engineers, and architects, from the public and private sectors and academia who specialized in building design and construction, FRC, MIVES, sustainability, and occupational risks in construction. During the seminars, weights were assigned using the AHP method (Saaty 1990), and real data were provided from projects to establish the value functions and scoring criteria for each indicator, measured in terms of attributes. Some of the participants facilitated data on construction costs and occupational risks during construction.

System Boundaries

The three requirements under consideration were those generally associated with sustainability, i.e., the economic, environmental, and social impacts (UN General Assembly 2005). The possibility was discussed of also including a technological requirement in order to consider aspects such as (1) the potential increase in structural reliability that can result from the ductile response of SFRC solutions, and (2) the increase in service beyond that established in the project due to the better performance of SFRC, compared with RC alternatives, in terms of corrosion. However, the use of such technological indicators was ultimately ruled out. This is because, although the experience with SFRC to date is satisfactory in terms of its behavior with regard to both service and ultimate limit states, the technical literature dealing with how to quantify these benefits is still limited. Consequently, any such assessment of the SFRC solution would lack sufficient objectivity.

The life-cycle analysis (LCA) stages considered were as follows: (1) extraction, transport, and in-plant processing of the materials used to fabricate construction materials, including all concrete components (cement, aggregates, water, and additives) and reinforcement materials (steel bars and/or fibers); (2) fabrication of the concrete; (3) transport, pouring, and vibrating operations for the concrete; and (4) transport and placement of the reinforcement. Possible repairs during construction due to local impacts or defects were also considered. Maintenance was not taken into account because concrete slabs are designed to avoid this need through the establishment of a minimum concrete cover and cement content, maximum water/cement ratios, and other measures meant to ensure a lack of maintenance requirements in normal service operations.

Based on experience and the results of the seminars, the unit considered representative and capable of integrating all the factors involved in assessing the sustainability index of any floor was the cubic meter of floor. Square meters could have been used instead, but, because all the analyzed alternatives have the same thickness, this does not affect the results and conclusions of the analysis. Comparing multiple facilities with different features (different slab thickness), square meters would be a better unit. In this regard, the proposed model is general and valid although the functional unit is adapted to other particular boundary conditions. The different viewpoints that might be offered by industry representatives (builders) and other stakeholders (private or public clients) could potentially alter the sustainability index of the assessed floor alternative. To deal with this aspect, different weighting scenarios can be proposed or established by end users of the tool. In this research project, the rating systems proposed in different sustainability assessment tools and guidelines were considered in order to develop a parametric study.

Requirement Tree and Components

The requirement tree defined in the proposed method (Table 2) includes the three aforementioned requirements (R). These requirements are divided into five criteria (C) and seven indicators (I). The indicators were selected to be representative (to discriminate between solutions) and independent of each other in order to ensure proper assessment and avoid overlap.

The economic requirement (R_1) is defined by a single criterion, namely, construction costs (C_1). This criterion is likewise assessed through a single indicator, total cost (I_1), which includes the costs associated with the manufacturing, transport, and placing of the materials, as well as the costs related to labor and any intermediate operations or facilities involving an additional cost.

The environmental requirement (R_2) is assessed through two criteria: resource consumption (C_2) and emissions (C_3). Resource consumption is defined as the consumption of reinforcing steel (I_2) and energy (I_3), whereas emissions consider only CO_2 equivalent emissions (I_4). Indicators I_3 and I_4 should take into account all the components of the structural concrete (cement, additions, additives, aggregates, and the reinforcement). Although additional indicators could be used, such as those defined by Casanovas-Rubio and Ramos (2017) and Casanovas-Rubio et al. (2016), those presented in Table 2 were considered the most representative and relevant in terms of environmental impact. Reinforcing steel consumption was assessed considering the total amount of steel required for the concrete slabs, including the longitudinal and transversal

Table 2. Requirement tree for sustainability analysis of concrete slabs

Requirement	Criterion	Indicator	Unit
R_1, economic ($\lambda_{R1} = 21\% - 33\%$)	C_1, construction costs ($\lambda_{C1} = 100\%$)	I_1, total cost ($\lambda_{I1} = 100\%$)	€/m^3
R_2, environmental ($\lambda_{R2} = 33\% - 60\%$)	C_2, resource consumption ($\lambda_{C2} = 33\%$)	I_2, steel consumption ($\lambda_{I2} = 33\%$)	kg/m^3
		I_3, energy consumption ($\lambda_{I3} = 67\%$)	MJ/m^3
	C_3, emissions ($\lambda_{C3} = 67\%$)	I_4, CO_2-eq emissions ($\lambda_{I4} = 100\%$)	kg/m^3
R_3, social ($\lambda_{R3} = 24\% - 33\%$)	C_4, occupational risks during construction ($\lambda_{C4} = 80\%$)	I_5, ORI ($\lambda_{I5} = 100\%$)	Weighted hour
	C_5, third-party effects ($\lambda_{C5} = 20\%$)	I_6, noise pollution ($\lambda_{I6} = 70\%$)	dB
		I_7, other inconveniences ($\lambda_{I7} = 30\%$)	Attribute

J. Constr. Eng. Manage., 2019, 145(7): 04019042

reinforcement for the RC solution and/or the steel fibers for the SFRC alternative. The energy consumption of the manufacturing materials was obtained from the available Inventory of Carbon and Energy databases (Hammond and Jones 2011). Finally, the emissions criterion was assessed by quantifying the amount of CO_2 released during the manufacture of the concrete and the steel required for the construction of the slab. Although energy consumption and CO_2-eq emissions during construction could also be considered, the results of the parametric analyses conducted showed that they account for less than 1.0% of those associated with the other phases; hence, they can be disregarded. Although water was included as a potential indicator in a former requirement tree and in other similar studies (de la Fuente et al. 2017b), it was finally not included in this study because (1) the composition of the concrete mixes can differ between alternatives to a certain extent, but the differences in the amount of water consumption are not significant; and (2) the same applies to the water consumed to produce the steel reinforcement, either rebars or fibers. If a potential user of the method proposed herein wanted to consider the water consumption indicator, this could be added in the requirement tree. In that case, the weights of the indicators within resource consumption criteria (C_2) should be modified accordingly.

The social requirement (R_3) is determined by means of two criteria: occupational risks during construction (C_4) and third-party effects (C_5). The occupational risks during construction of the different stages of the construction process are assessed by means of the occupational risk index (ORI) (I_5) defined by Casanovas et al. (2014). In order to calculate the ORI, the different activities of the construction work involving risk and the total amount of time devoted to each were analyzed. The third-party effects (C_5) are evaluated with two indicators: noise pollution (I_6), which is mainly due to the vibration operations for the concrete, and other inconveniences (I_7) causing discomfort to pedestrians or affecting traffic. An indicator considering the employment generation also could have been considered here, but it was finally discarded by the experts in the seminars.

Construction time, which is considerably shorter for SFRC solutions than for the RC alternatives, was not considered as an independent indicator. Although the time variable is directly considered in indicators I_1 and I_5, it could also be considered in a separate indicator to address aspects such as (1) risk of construction stoppages (reinforcement placing) due to rain; or (2) the delivery time of the structure. These two indicators could be included in the economic requirement (R_1) in those cases for which the time variable is a relevant and sensitive factor (e.g., shopping centers).

Value Functions

Value functions were assigned to the previously described indicators in order to assess the sustainability index (I_s) of the alternatives, which ranges from 0.0 to 1.0 and is usually below 0.8. This approach was already applied in previous studies (Alarcon et al. 2011; Hosseini et al. 2015; Reyes et al. 2014; San-Jose and Cuadrado 2010; San-Jose and Garrucho 2010). This function transforms the physical units of each indicator (e.g., €/m^3, kg/m^3, or dB) into dimensionless values ranging from 0 to 1. These values represent the sustainability or satisfaction of each indicator. The general form of a value function, which enables assessment of the indicator's value or satisfaction ($I_{\rm ind}$), is

$$I_{\rm ind}(X) = A + B\left[1 - e^{-K_i\left(\frac{|X_{\rm ind}-X_{\rm min}|}{C_i}\right)^{P_i}}\right] \quad (1)$$

where B = value of $I_{\rm ind}$ for $X_{\rm min}$; $X_{\rm min}$ = minimum abscissa value of the indicator interval assessed; X = abscissa value for the indicator assessed; P_i = shape factor that defines whether the curve is concave ($P_i < 1$), convex ($P_i > 1$), linear ($P_i = 1$) or S-shaped ($P_i > 1$) (Fig. 1); C_i approximates the abscissa at the inflexion point; K_i tends toward $I_{\rm ind}$ at the inflexion point; $X_{\rm max}$ = abscissa value of the indicator that gives a response value of 1 for increasing value functions; and B = factor that prevents the function from exceeding the range (0, 1)

$$B = [1 - e^{-K_i[(|X_{\rm max}-X_{\rm min}|)/C_i]^{P_i}}]^{-1} \quad (2)$$

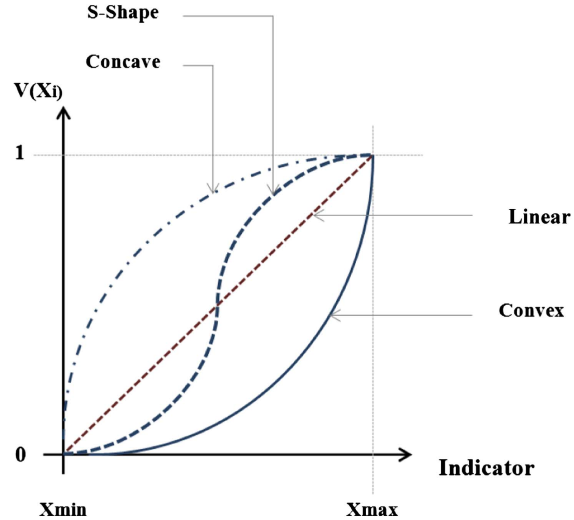


Fig. 1. Value function shapes.

Weight Assignment

The weights (λ) of each criterion and indicator of the requirement tree (Table 2) were assigned based on similar studies in the literature (Awadh 2017; Diaz-Sarachaga et al. 2016; Politi and Antonini 2017; Pons et al. 2016). The weights of the requirements were considered variable and assigned according to the magnitudes proposed in the most widely used sustainability rating system tools for buildings (Table 3).

The values assigned to each requirement in Table 3 were grouped into the three main sustainability pillars according to the authors' criteria. This decision was made because none of the considered sustainability rating systems explicitly categorizes the indicators into only these pillars. For instance, the DGNB system proposes an equal distribution (22.5%) for the three pillars (67.5%) and a 32.5% share for a group of indicators categorized as Others (DGNB 2018). The authors redistributed this weight to the three main pillars in order to apply the requirement tree presented in Table 2. The same assumption was made with the other rating

Table 3. Requirement weight distribution according to various sustainability performance assessment tools (%)

Requirement	LEED	BREEAM	DGNB
Economic (λ_{R1})	27	21	33
Environmental (λ_{R2})	49	60	33
Social (λ_{R3})	24	25	33

Note: The LEED, BREAM, and DGNB tools assign weights of 5%, 10%, and 32.5%, respectively, to the indicators grouped as Others not included in the three requirements. The authors redistributed these weights to the three main pillars in order to apply the requirement tree of Table 2.

J. Constr. Eng. Manage., 2019, 145(7): 04019042

systems, which assign weights of 5% (LEED, USGBC 2015) and 10% (BREEAM 2016) to the indicators grouped as others.

The weight distribution in Table 3 suggests an increasing concern with regard to natural resource scarcity and the consequences of global warming, factors falling under the environmental requirement (weights from 33% to 60%), whereas relatively less importance is given to economic aspects (<33%). The relatively low weights assigned to the social aspects (24%–33%) could be the result of the demanding safety regulations already in place and other requirements the application of which guarantees a high degree of social satisfaction without the need to impose high values of λ_{R3} in sustainability assessment systems.

Case Study: Office Building in Guipúzcoa (Spain)

Description of Structure

The structure selected for the case study is the project for the headquarters office building of the company LKS in Arrasate-Mondragón (Guipúzcoa), a pioneering experience in Spain with regard to the use of steel fibers as the main reinforcement in concrete slabs. All data corresponding to the geometry, materials, and costs used in the present study were obtained from Maturana (2013).

The building has four floors and a semibasement providing access to the offices. The four façades face the cardinal points. The construction includes the basement (Floor-1), the ground floor, and three additional floors. The dimensions of the basement below ground level are 43.0×20.0 m, whereas at ground level they are 33.0×20.0 m. The building has a total built-up surface of 3,506 m^2, of which 862 m^2 corresponds to the basement and 661 m^2 to each of the other four floors above ground.

The geometry consists of a grid of a maximum of 8.0×8.0 m with circular (diameter ranging from 45 to 60 cm) and rectangular (35×45 cm and 50×60 cm) RC columns that support flat slabs with a thickness of 30 cm. This type of floor is constructed around a central core containing the building's facilities and services, which means the slabs have openings. The columns are aligned horizontally in Sections A, B, C, and D and are separated by 8.0, 4.5, and 5.4 m, respectively; they are aligned vertically in Sections 1, 2, 3, 4, and 5 and separated by 7.8 m. The largest areas of the grid (8.0×7.8 m) are located between Sections A and B.

The slab for the basement (Floor-1) has a layout similar to that of ground floor and Floors 1, 2, and 3, but includes two more sections, adding an additional 10.0 m to the building's lateral dimension. Each floor of the building has a maintenance terrace that extends 1.15 m from the concrete structure. These terraces are made of a metal structure.

Alternatives Analyzed for Concrete Flat Slabs

Steel Bar–Reinforced Concrete (Original Design)

The RC solution consisted of concrete with a characteristic compressive strength of 30 N/mm^2 at 28 days ($f_{ck,28}$) reinforced with corrugated steel bars with a yield strength of 500 N/mm^2. The reinforcement design followed the safety format proposed in Spanish Structural Concrete Guideline EHE-08 (CPH 2008), considering a permanent load of 8.0 kN/m^2 (including self-weight) and two independent live loads with magnitudes of 2.0 and 3.0 kN/m^2. An additional 10.0 kN/m^2 was assumed in the parking areas.

The reinforcement layout (Table 4) consisted of Φ12-mm base reinforcement (BaR) distributed as a 150×150 mm grid located on both the top and bottom faces of the slab across the entire surface of all the floors, intended to bear tensile stresses caused by bending moments. Additional local reinforcements were also designed: (1) bottom face (BR) at midspan for positive bending moments; (2) top face (TR) on columns for negative bending moments; (3) external and internal perimeters (RR) of the slab to bear coupled torsion and bending effects; and (4) punching shear reinforcement (PR) around the slab–column intersections. The average amount of reinforcement for the RC solution was 109 kg/m^3, with the base reinforcement accounting for 71%.

Table 4. Amount of reinforcement for traditional RC flat slab alternative

Reinforcement	Ground floor	Floor 1	Floor 2	Floor 3	Roof floor
BaR (kg)	19,565	14,550	14,550	14,550	14,550
BR (kg)	1,366	210	210	210	1,125
TR (kg)	3,479	2,075	2,075	2,075	2,733
PR (kg)	2,820	2,456	2,456	2,456	2,456
RR (kg)	781	781	781	781	781
Total (kg/m^3)	111	107	107	107	117

Self-Compacting Steel Fiber–Reinforced Concrete (Constructed Solution)

The alternative solution was based on the substitution of the steel rebars with steel macrofibers, maintaining the 30-cm slab thickness, as well as the $f_{ck,28}$ design of 30 N/mm^2. The main goal was to reduce the associated cost of the structure, which is significantly affected by labor and by the preparation and placement of traditional reinforcement. Crimped steel (yield strength 900 N/mm^2) macrofibers with a circular cross-section diameter of 1.3 mm and a length of 50 mm (aspect ratio 38) were used. To withstand the same design loads while guaranteeing the same reliability level accepted for RC structures, a postcracking residual tensile strength (f_{ctR}) of 2.2 N/mm^2 was established based on a plastic analysis carried out according to the Johansen theory (Johansen 1962). This theory is accepted in the Spanish EHE-08 (CPH 2008) for FRC structures. According to the results of the material predesign and production quality control tests, this mechanical performance can be achieved with 100 kg/m^3 of fibers. However, self-compacting concrete must be used to ensure the workability of material with such a large amount of fibers. Macro synthetic fibers could also be considered in these applications; however, specific studies of both cracking and the permanent load level must be carried out before they can be reliably used (Pujadas et al. 2017).

Complementary use of steel bars was required in certain specific areas of the slabs, such as corners, openings, perimetral cantilevers, and cantilevers with façade loads (Table 5). Furthermore, additional antiprogressive collapse (APC) reinforcement (Mitchell and Cook 1984) was included to prevent local failures in the slab that could lead to the collapse of the entire slab. This reinforcement provides additional structural safety, because the APC reinforcement can bear the permanent loads and a percentage of the live loads to which the slab might be subjected. The reinforcement layout was grouped into reinforcement for positive moments along the edges of the grid (ER), complementary reinforcement in certain areas (CR), the APC reinforcement, and steel fibers.

The APC reinforcement is a redundant reinforcement that could also have been included in the RC solution. If this reinforcement were excluded from the calculations, the amount of traditional reinforcement in this solution would be significantly reduced (on average, 17 kg/m^3). Because there have been no previous experiences with the use of steel fibers as the primary reinforcement in building column–supported flat slabs in Spain, the final constructed solution included the APC reinforcement as a precaution.

Table 5. Amounts of reinforcement for SFRC flat slab alternatives

Reinforcement	Ground floor	Floor 1	Floor 2	Floor 3	Roof floor
ER (kg)	512	1,025	1,025	1,025	2,131
CR (kg)	2,233	1,930	2,058	1,832	2,674
APC (kg)	3,103	2,627	2,627	2,627	4,378
Total steel rebars (kg/m^3)	23	29	29	29	49
SF (kg/m^3)	100	100	100	100	100
Total steel rebars and fibers (kg/m^3)	123	129	129	129	149

Note: ER = reinforcement for positive moments along the edges of the grid; CR = complementary reinforcement in certain areas; APC = antiprogressive collapse reinforcement; and SF = steel fibers.

Therefore, there could be two alternatives based on the use of steel fiber–reinforced self-compacting concrete (SFRSCC) with 100 kg/m^3 fiber and steel bar reinforcement in amounts of (1) 34 kg/m^3 (including APC), which was the solution ultimately constructed (SFRSCC + APC), or (2) 17 kg/m^3, which represents extra local reinforcement (SFRSCC).

Concrete Mixes

The concrete mixes considered for both the initial RC solution and the SFRSCC solution are listed in Table 6. The RC concrete mix was the typical mix used in the location proposed by the consulted stakeholders. The differences in the mixes reflected the need to compensate the loss of workability of the fresh concrete due to the addition of fibers. Therefore, there were differences in the cement, water, and aggregate contents. The fibers were added to the coarse aggregate conveyer belt to guarantee a homogeneous distribution. A total of 24 boxes (25 kg each) was added to the 6-m^3-capacity trucks used to mix and transport the concrete. Additionally, fly ash was added to the mix with steel fibers in order to reduce the amount of cement and therefore the cost, the energy consumption, and the CO_2 emissions. These indicators are considered in the requirement tree (indicators I_1, I_3, and I_4, respectively), and the method proposed in this paper can objectively consider this aspect.

Indicator Quantification

The indicators were quantified according to the data reported by Maturana (2013), particularly those related to costs (I_1) and materials ($I_2 - I_4$). The CO_2-eq emissions (I_3) and energy consumption (I_4) involved in the LCA processes for the materials used to produce the concrete (Table 6) and for its reinforcement (Tables 4 and 5) were calculated using the mean values listed in the Inventory of Carbon Energy version 2.0 (Hammond and Jones 2011). The CO_2-eq emission and energy consumption ratios for the steel fibers were those proposed in ITAtech (2016). The risks during construction were quantified by means of the occupational risk index (ORI) (I_5) (Casanovas et al. 2014). The ORI of a construction process is defined as

$$\mathrm{ORI} = \sum_i \mathrm{ORI}_i = \sum_i W_i \times E_i \tag{3}$$

where i = risk associated with an activity; ORI_i = occupational risk index of risk i; E_i = exposure of the workers to risk i expressed in units of time (hours); and W_i = importance of risk i, which depends on the likelihood or probability of occurrence of an accident (P_i) given risk i and the severity of its most probable consequence (C_i)

$$W_i = \frac{P_i \times C_i}{\max\{P_i \times C_i\}} = \frac{P_i \times C_i}{1000} \tag{4}$$

For the specific structural typology analyzed in this research, three specific risks were evaluated in addition to those presented by Casanovas et al. (2014). These risks were (1) same-level falls when walking over rebars; (2) structural risk or macrorisk when building conventional slabs; and (3) structural risk or macrorisk when building SFRC slabs. Structural risk or macrorisk was defined by Casanovas et al. (2014) as the risk of accident due to the failure of the structure or an auxiliary element during construction. It is caused by errors in the design, execution, or management of the structure under construction rather than by a lack of preventive measures against occupational safety hazards. These risks were assessed according to the ratings of probability and severity presented in Tables 1 and 2 in Casanovas et al. (2014) (adapted from Fine 1971). The results are listed in Table 7. Although the SFRC solution was designed according to the same structural reliability level accepted for the RC solution, a slightly higher probability of structural accident was assumed for the SFRC solution due to its novelty.

The activities carried out to build the slabs in the case study and the associated risks and risk importance (W) were identified and are presented in Table 8 together with the exposure time and ORI results for the analyzed alternatives. The following hypotheses arising from the technical seminars were established:

- It was agreed that steel worker productivity ranges from 200 to 250 kg/person/h for 500–700 m^2 floor slabs. The maximum value was assumed for this study, which benefits the RC solution. Based on the amounts of steel in Tables 4 and 5, the total time devoted to steel preparation and placement was 441 h (RC), 127 h (SFRSCC + APC), and 66 h (SFRSCC).
- 60% of the total exposure time of workers to the risk of falls to lower levels corresponds to falls through outside openings in facades, and the remaining 40% corresponds to falls through internal hollow spaces in the slabs.
- A total of 3 h are required to move 18,000 kg of bars from the truck to the floor of the building under construction using a crane; 1 extra hour is required for every 18,000 kg of bars if they are stockpiled before being lifted.

Table 6. Concrete mixes for RC and SFRSCC alternatives

Component	Characteristics	RC	SFRSCC
Cement (kg/m^3)	CEM I	300	—
	CEM II/BM-VLS 42.5R	—	400
Aggregates (kg/m^3)	—	1,905	1,850
Water (kg/m^3)	—	165	185
Water/cement	—	0.55	0.41
Additions (kg/m^3)	Fly ash	—	120
Fibers (kg/m^3)	Steel	—	100
Admixture (L/m^3)	Superplasticizer	1.6	4.6

Table 7. Probability, consequence, and importance ratings for risk of each activity

Risk—activity	P	C	W
Same-level falls: walking over rebars during placement and concrete pouring	6.00	1.0	0.006
Structural risk or macrorisk: conventional slabs	0.75	50.0	0.038
Structural risk or macrorisk: SFRSCC slabs	1.00	50.0	0.050

Note: Values are dimensionless.

Table 8. ORI results for each alternative analyzed

Risk—activity	W (dimensionless)	Exposure time, E (h)			$W \times E$ (weighted hours)		
		RC	SFRSCC + APC	SFRSCC	RC	SFRSCC + APC	SFRSCC
Same-level falls—walking over rebars during placement and concreting	0.006	520.6	207.2	146	3.124	1.243	0.875
Falls to lower levels—work at heights or depths of more than 2 m: outside openings in façades	0.060	1,008.7	632.7	558.9	60.523	37.960	33.536
Falls to lower levels—work at heights or depths of more than 2 m: hollow spaces	0.075	672.5	421.8	372.6	50.436	31.634	27.947
Collision with or entrapment by a moving load due to its movement or detachment—mechanical load handling: cranes and self-propelled industrial trucks	0.065	18.4	6.4	3.5	1.193	0.419	0.228
Blows to upper and lower limbs—manual load handling: installation of rebars	0.021	440.6	127.2	66.0	9.253	2.672	1.381
Collision with or running over by heavy equipment or heavy-goods vehicles—work with heavy equipment or heavy-goods vehicle: concrete mixer truck	0.068	8.0	8.0	8.0	0.544	0.544	0.544
Collision with or running over by heavy equipment or heavy-goods vehicles—work with heavy equipment or heavy-goods vehicle: concrete pump truck	0.068	8.0	8.0	8.0	0.544	0.544	0.544
Traffic accident—transport of elements to the construction site: concrete	0.040	28.0	28.5	28.5	1.120	1.140	1.140
Traffic accident—transport of elements to the construction site: steel (rebars)	0.030	5.6	1.9	0.9	0.168	0.056	0.028
Structural risk or macrorisk: RC slabs	0.038	1,681.2	—	—	63.886	—	—
Structural risk or macrorisk: SFRSCC slabs	0.050	—	1,054.5	932	—	52.723	46.578
ORI					190	129	113

- The distance from the concrete plant to the site was measured at 2.8 km (5-min trip); 6-m^3 mixer trucks are used to transport the concrete this distance.
- Both the concrete mixer and pumper trucks move around the construction site 1/10 (10%) of the time dedicated to concreting.
- Bars come from a plant located 24.7 km from the construction site (28-min trip). A truck with a maximum authorized weight limit of 24,000 kg was used. A total of 18,000 kg/trip was assumed. Therefore, a total of six (RC), two (SFRSCC + APC), and one (SFRSCC) trips are required.

The results of the thorough quantification of the indicators considered in the requirement tree (Table 2) for each flat slab alternative analyzed are listed in Table 9. From the results presented in Table 9 the following conclusions can be drawn:

- The SFRSCC alternatives entail a cost reduction of 11.7% (+APC) or 15.9% with regard to the RC solution, due to the optimization of both labor and construction time. The net productivity achieved with the SFRSCC+APC flat slab solution was 17.5 m^2/h (1 level/week); this entails a 37% reduction in the required time compared with the RC alternative. This cost reduction trend becomes more attractive as the building height increases.
- The amount of steel increases 22.9% (SFRSCC + APC) and 7.3% (SFRSCC) compared with the RC flat slab solution because fiber reinforcement is less efficient in terms of its ultimate limit state at the sectional level than bar reinforcement (placed where the maximum tensile stresses are expected). Nevertheless, numerous full-scale tests of supported slabs according to different configurations have shown that the actual load-bearing capacity is considerably higher than that considered in the design (Blanco et al. 2015a; Pujadas et al. 2012). The latter is based on partial safety factors and material characterization results from small-scale tests that might not be representative of the real behavior of SFRC slabs in service. Therefore, extra measures, such as the inclusion of an APC reinforcement, are used to err on the side of caution. Reinforcement and fiber content optimization will come as designers get used to this technology and more representative design methods are proposed in the guidelines.
- The fact that a higher total amount of steel is required for the SFRSCC alternatives also leads to their greater energy consumption and CO_2-eq emissions. Furthermore, a rate of 2.4 kg CO_2-eq/kg was considered for the steel fibers, whereas 1.9 kg CO_2-eq/kg was assumed for the steel bars. The former is the highest value found in the databases and was used for this study due to the wide range of variability observed for this ratio. The latter is the rate proposed by Hammond and Jones (2011) for world average bars with 39% recycled steel. SFRSCC also

Table 9. Indicator results obtained for each analyzed flat slab alternative

Indicators	RC	SFRSCC + APC	SFRSCC
I_1. Total cost (€/m^3)	521	460	438
I_2. Steel consumption (kg/m^3)	109	134	117
I_3. Energy consumption (MJ/m^3)	3,866	5,004	4,637
I_4. CO_2-eq emissions (kgCO_2-eq/m^3)	435	561	530
I_5. Occupational Risk Index (ORI)	190	129	113
I_6. Noise pollution (dB)	80	<60	<60
I_7. Other inconveniences	Acceptable	Remarkable improvements over RC	

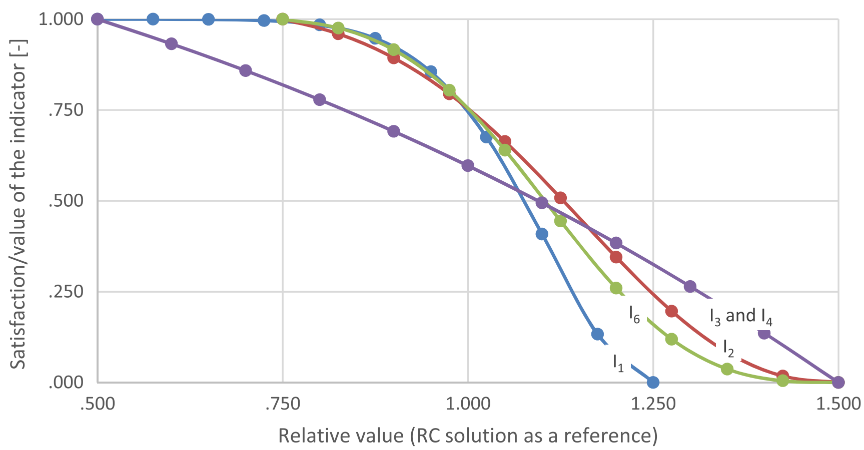
requires 33% more cement than the reference concrete dosage (Table 6).

- The SFRSCC alternatives ($113 \leq \text{ORI} \leq 129$) are safer than the RC solution ($\text{ORI} = 190$). The former perform better for most of the risks (Table 8) due to the lower exposure time to the risk entailed in the use of a concrete reinforcement (fibers) added directly at the plant. With regard to the rest of the risks (collision with or running over by the concrete mixer truck or concrete pump truck, and traffic accident due to the transport of the concrete to the site), the analyzed alternatives had equivalent performance.
- Suitable concrete compaction is achieved with vibrators in the RC flat slab solution. Those most often used in building construction produce noise intensities of up to 80 dB. In contrast, SFRSCC does not require any additional vibration to achieve the same concrete compaction standards. This drastic reduction in the noise pollution is an important positive outcome for buildings being constructed in urban areas.
- There was a noticeable decrease in traffic disruptions (reduction to one-third the total number of truck trips and the time spent occupying public areas). Moreover, it was estimated that 1,681 h (37 days) were needed to build the concrete slabs for the RC alternative, whereas 1,055 h (27 days) were needed for the SFRSCC + APC constructed solution and 932 h (25 days) for the SFRSCC alternative. This means that the SFRSCC + APC and SFRSCC alternatives entailed a 37% and 45% reduction in construction time with regard to the RC. This further entails a social benefit in terms of other types of inconveniences (e.g., visual disturbances or dust). This, however, entails lower employment generation, which was not considered in this analysis.

Satisfaction Functions

The last step of the MIVES method consists of defining value functions for each indicator that make it possible to convert dimensional quantities into nondimensional magnitudes ranging from 0.00 to 1.00 representing satisfaction. The constitutive parameters calibrated for each value function [according to Eq. (1)] are shown in Fig. 2. The RC solution was taken as a reference and the indicator magnitudes of the alternatives were expressed relative to it (except Indicator I_5). The criteria used to define the value functions were

- For the cost (I_1), reinforcement steel (I_2), risk during construction (I_5), and noise pollution (I_6) indicators, a reference



Indicator	Function	X_{max}	X_{min}	C	K	P
I_1. Total cost	DS	1.25	0.50	1.00	20.00	1.90
I_2. Reinforcing steel	DCx	1.50	0.75	1.20	9.50	2.30
I_3. Energy	DS	1.50	0.50	7.00	1.00	0.50
I_4. CO_2-eq emissions	DS	1.50	0.50	8.00	7.00	1.00
I_5. Occupational risk during construction	DL	190	50	Decreasing Linear (0.75 – 1.00)		
I_6. Noise pollution	DS	1.25	0.50	1.00	11.00	3.00
I_7. Other inconveniences	DS	Unacceptable: < 0.50; Acceptable: 0.50 (RC reference); Noticeable improvements over RC: 0.50 – 0.75; Remarkable improvements over RC: 0.75 – 1.00				

Note: DS: decreasing S-shape; DCx: decreasing convex; DL: decreasing linear

Fig. 2. Value functions and respective constitutive parameters.

satisfaction value of 0.75 was set for the RC solution due to the widespread use of this technology in the building sector. For Indicators I_1, I_2, and I_6, maximum satisfaction (1.00) is achieved for a 50% reduction, whereas minimum satisfaction (0.00) is achieved for a 50% increase for I_2 and I_6 and a 25% increase for I_1 (due to the high competitiveness).

- The satisfaction function for the occupational risks during construction indicator (I_5) was limited to ORI values of 50–190, with satisfaction values linearly distributed from 1.00 to 0.75, respectively. Here, too, the RC solution was used as the reference (ORI = 190, 0.75). If ORI > 190 is achieved, the satisfaction values can be interpolated. The designers and stakeholders must limit the maximum ORI according to national regulations regarding construction safety.
- The same satisfaction function was established for both the energy consumption (I_3) and CO_2-eq emissions (I_4) indicator. To promote environmentally friendly practices, a 0.60 satisfaction value was assumed for the RC solution, and maximum and minimum satisfactions are reached for a 50% decrease or increase, respectively.
- For the other inconveniences (I_7) indicator, satisfaction will mostly depend on the culture, country, regulations, and other aspects. The satisfaction function is graded considering the attributes. Once again, the RC solution was used as the reference, with a satisfaction value of 0.50 to promote improvement.

This set of value functions can be calibrated and adapted to other stakeholder preferences, making it possible to take into account other economic situations or environmental and social perceptions aligned with specific national strategies. In this regard, the value functions proposed herein might be representative of the framework of a developed country in a good economy firmly committed to promoting better environmental and social practices.

Sustainability Indexes (I_s) for Each Flat Slab Alternative

Based on the defined requirement tree (Table 2), the indicators quantified for the three analyzed alternatives (Table 9), and the established satisfaction functions (Fig. 2), the sustainability index (I_s) of each alternative (Table 10) can be assessed in accordance with the different rating systems presented in Table 2.

The three construction alternatives for the column-supported flat slabs in the case study building yielded sustainability indexes between 0.55 [SFRSCC + APC (BREEAM 2016)] and 0.75 [SFRSCC (DGNB 2018)], with mean values of I_s ranging from 0.62 (SFRSCC + APC) to 0.69 (RC and SFRSCC). From these findings, the following aspects can be highlighted:

- Although all three alternatives were found to have acceptable sustainability indexes (>0.60), better sustainability performance can still be achieved. Therefore, the environmental requirement should be prioritized in the design and construction phases in order to effectively increase I_s. The use of SFRSCC with recycled aggregates is currently being studied in order to improve this aspect (Ortiz et al. 2017).
- In this particular case, the slight differences found for the average values of I_s (a range of 0.07) indicate that all three alternatives performed quite similarly in terms of sustainability. Therefore, from a decision-making perspective, other aspects (e.g., opportunity costs associated with the use of new technologies, the experience of local concrete producers with SFRC mixes, and employment generation) must be taken into account. The differences in I_s would be more noticeable if the building were taller and the construction time for the structure were a major constraint.

Conclusions

This paper proposes a method for assessing the sustainability performance of column-supported slabs for buildings based on the MIVES tool. The method makes it possible to compare and prioritize material technologies and construction alternatives while considering the three main pillars of sustainability and minimizing subjectivity in the decision-making process.

The method was applied to the real case of an office building in Spain originally designed with RC flat slabs but ultimately constructed with a steel fiber–reinforced self-compacting concrete solution, including an antiprogressive collapse reinforcement for additional structural safety reasons. The following conclusions can be drawn regarding the particular case studied:

- The SFRSCC + APC solution led to an 11.7% cost reduction compared to the RC alternative. Moreover, a productivity ratio of 17.5 m^2/h (1 floor/week) was achieved, entailing a 37% reduction in construction time with regard to the latter.
- This reduction in labor hours likewise reduced the exposure time to occupational risks compared with the RC solution. This aspect was included in the MCDM model by means of the occupational risk index presented by Casanovas et al. (2014). It could have also been included in terms of employment generation.
- The environmental impact of the SFRSCC solutions was higher due to the greater steel consumption (22.7% for the SFRSCC + APC solution and 7.3% for the SFRSCC solution). However, these steel consumption ratios could be notably reduced by using the steel fibers available today and also by reducing the additional safety measures included in the design of the SFRSCC solutions analyzed here (e.g., avoiding redundant use of APC reinforcement and/or the consideration of probable and representative failure mechanisms of the slab).
- According to the value calculated in Table 10, RC seems to be equivalent to or slightly better than the SFRSCC solutions in terms of overall sustainability indexes. However, when higher weights were assigned to the social requirement, as in the case of DGNB, the performance of the SFRSCC solutions increased due to the low noise pollution and reduced third-party effects.

The construction sector lacks sustainability rating tools to assess structural building components separately (e.g., columns, floors, panels, and façades). The existing tools are meant to cover the whole building, and thus cannot account for relevant indicators associated with the structural components. This paper presents a new tool, based on the MIVES approach, specifically designed to assess the sustainability of slabs. New methods particularly oriented to structural elements or products, such as the one presented herein, are very useful for assessing the sustainability of new construction technologies prior to their implementation. Moreover, SFRC has had limited use in structural building slabs and had not been analyzed from a sustainability perspective including environmental, social and economic aspects for this particular application.

Table 10. Values obtained for each analyzed flat slab alternative

Rating criterion	RC	SFRSCC + APC (constructed)	SFRSCC
LEED	0.69	0.61	0.67
BREAM	0.69	0.55	0.64
DGNB	0.69	0.69	0.75

Note: The authors redistributed the weighs assigned to the indicators grouped as Others in LEED, BREAM, and DGNB tools between the three main pillars of the requirement tree in Table 2.

For the moment, the model does not consider the employment generation of the different alternatives. As future research, an indicator considering the employment generation and related aspects such as temporariness, income level, skill and knowledge level, and so on could be developed and included in the model. This may slightly affect the results depending on the defined indicator and assigned weights. If the indicator of employment generation were defined as the total working hours in the construction work, the global sustainability of the fiber-based solutions would be lower because its working hours are lower than those of the conventional solution. Another weakness of the model is that it can be time consuming and some data can be difficult to obtain.

The first recycled structural fibers are appearing in the market. Their structural contribution is still not clear, but it is a matter of time until these fibers can be used in high structural responsibility applications. The proposed model is also valid to assess the sustainability of alternatives with recycled fibers by considering the indicators of cost, energy consumption, and CO_2-eq emissions accordingly.

Finally, the authors have noticed that, as usually happens with incipient construction technologies, there is still a certain resistance toward the use of fiber-reinforced concrete in column-supported flat slabs due to the lack of experience in its design and the additional measures (redundant reinforcement) used in the earliest applications, which would seem to offset the economic and construction time benefits observed with regard to the traditional RC solution. For fiber-reinforced concrete alternatives to become more widespread, it is necessary to demonstrate their structural reliability to both the scientific and technical communities through more real-scale applications coupled with sustainability analyses performed with multicriteria decision-making tools similar to the one presented here.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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