Journal of Construction Engineering and Management 2019, 145(7): 04019042
DOI: 10.1061/(ASCE)CO.1943-7862.0001667

Sustainability of column-supported reinforced concrete slabs: fibre reinforcement as an alternative

de la Fuente A[a*], Casanovas-Rubio MM[b*], Pons O[c], Armengou J[d]

[a] Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya

[b] Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya

[c] Department of Architectural Technology, Universitat Politècnica de Catalunya

[d] School of Architecture, Universitat Internacional de Catalunya

Abstract. Fibre-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 favourable 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 optimise the design whilst guaranteeing the required reliability levels. However, in some cases, fibres 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, façades). This paper presents a new method that can be used to assess the sustainability of concrete slabs by means of a multi-criteria decision-making approach including fibre-reinforced concrete. To this end, it uses rigorous analyses of current concrete slab technologies and sustainability assessment tools. Criteria, indicators, weights and value functions have been specifically selected, defined and calibrated for this research.

Keywords: Building; Environment; MIVES; Slabs; Steel-Fibre-Reinforced Concrete; Sustainability.

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 will focus 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).

* Corresponding author. Universitat Politècnica de Catalunya. Jordi Girona 1-3, 08034, Barcelona, Spain.

E-mail: mar.casanovas@upc.edu

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 out of wood (AWC, 2015), composite (SDI, 2017) or reinforced concrete (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 industrialised (AWC, 2015) or completely prefabricated. Finally, with regard to structural typology, slabs can be unidirectional, bidirectional or multidirectional, solid or hollow-core (AWC, 2015).

More recently, fibre-reinforced concrete (hereinafter, FRC) has emerged as an alternative cement-based material for structural applications. Several technical advantages of using steel-fibre-reinforced concrete (hereinafter, SFRC), in particular, have been reported, including cracking control, ductility and impact resistance enhancement, amongst others. Additionally, as fibres are added directly at the concrete plant, on-site labour and time needs decrease significantly. In this regard, where required, concrete steel-bar reinforcement operations (handling and placing) can be minimised in order to optimise execution time. Occupational safety is thus also improved due to the minimisation 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., 2010); tunnel linings (Chiaia et al., 2009; de la Fuente et al., 2012b; Liao et al., 2015a, 2015b; Meda et al., 2014); and others (e.g. wind turbine supports, water storage tanks, retrofit and repair applications).

Additionally, SFRC has been successfully employed in flat slabs in real buildings (**Table 1**) and its structural behaviour has been extensively researched by means of full-scale tests (Blanco et al., 2015a, 2015b; 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, 2014), and the examination of design aspects (Destrée, 2004; Destrée and Mandl, 2008; Maturana, 2014; Maturana et al., 2010). In these experiences, span lengths up to 8.00 m have been achieved using steel macro-fibres 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 up construction. Compressive concrete strengths ranging from 30 to 60 N/mm^2 are used. Furthermore, there is already a technical recommendation, the ACI 544.6R-15 (ACI, 2015) specifically oriented towards facilitating the design of SFRC pile-supported flat slabs.

Although both the experimental programmes 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, as only some of the benefits have been reported. In fact, in most cases the decision of whether to use steel fibres 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, there are several methods and tools that make it possible to take into account the three main pillars of sustainability; for instance, generic rating tools such as: Building Research Establishment Environmental Assessment Method (BREEAM, 2016), 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, whilst 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, 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 behaviour 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 has not revealed a specific method to evaluate the sustainability of building slabs.

In light of the above, the present paper aims to propose a method for assessing the sustainability of reinforced concrete slabs using MIVES (from the Spanish, Integrated Value Model for Sustainability Assessment, Aguado et al., 2012, Alarcon et al., 2011, Villegas et al., 2010). This method would make 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 has been paid to occupational safety issues in construction and the assessment thereof. To this end, a novel multi-criteria risk assessment method

(Casanovas et al., 2014) has been coupled with MIVES in order to objectively consider the different occupational risks entailed in each of the analysed column-supported slab construction methods.

As a case study and example of application, the method proposed here is 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-fibre-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 multi-criteria decision-making (MCDM) approach that enables the sustainability assessment of processes and products minimising 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 maximise both the robustness and reliability of the results (del Caño et al., 2012, 2016). Among other possible methods, MIVES has been 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 the 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 organised to define the requirement tree and its criteria, indicators, weights, and value functions. The seminars consisted of 9 experts, civil and industrial engineers, and architects, from the public and private sectors and academia specialised 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 are 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 to 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 behaviour 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 fibres); (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 since 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 metre (m^3) of floor. Square metre (m^2) could have been used instead, but, as all the analysed alternatives have the same thickness, this does not affect the results and conclusions of the analysis. When comparing across multiple facilities with different features (different slab thickness), square metre (m^2) would be a better unit. In this regard, it must be remarked that 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 parameter study.

Requirement tree and components

The requirement tree defined in the proposed method (**Table 2**) includes the three abovementioned requirements (R). These requirements are divided into 5 criteria (C) and 7 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 labour 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* considered only CO_2 equivalent emissions (I_4). 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 in 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 reinforcement for the RC solution and/or the steel fibres 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. Whilst energy consumption and CO_2-eq emissions during construction could also be considered, the results of the parametric analyses conducted show 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 since: (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 fibres. Should 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 (C2) 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 in 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 one were analysed. The *third-party effects* (C_5) are evaluated with two indicators: *noise pollution* (I_6), 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 could have also been considered here, but it was finally discarded by the experts in the seminars.

Construction time, which is considerably shorter for SFRC solutions than 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 stops* (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 centres).

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, dB) into dimensionless values ranging from 0 to 1. These values represent the sustainability or satisfaction of each indicator. Equation 1 shows the general form of a value function, which enables assessment of the indicator's value or satisfaction (I_{ind}).

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

In Equation 1, B is the value of I_{ind} for X_{min}; X_{min} is the minimum abscissa value of the indicator interval assessed; X is the abscissa value for the indicator assessed; P_i is a 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) (see Fig. 1); C_i approximates the abscissa at the inflexion point; K_i tends towards I_{ind} at the inflexion point; B, the factor that prevents the function from exceeding the range (0, 1), is obtained by Equation 2; and X_{max} is the abscissa value of the indicator that gives a response value of 1 for increasing value functions.

$$\boldsymbol{B} = \left[1 - e^{-\boldsymbol{K_i}\left(\frac{|\boldsymbol{X_{max} - X_{min}}|}{\boldsymbol{C_i}}\right)^{\boldsymbol{P_i}}}\right]^{-1} \quad (2)$$

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) and by the authors (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 categorises 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 categorised as 'Others' (DGNB, 2018). The present 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 systems, which assign weights of 5% (LEED, USGBC, 2015) and 10% (BREEAM, 2016) to the indicators grouped as 'Others'.

The weight distribution shown 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 33-60), whilst 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 whose application 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 the 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 fibres 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 4 floors and a semi-basement 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 x 20.0 m, whereas at ground level they are 33.0 x 20.0 m. The building has a total built-up surface of 3,506 m^2, of which 862 m^2 correspond 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 x 8.0 m with circular (diameter ranging from 45 to 60 cm) and rectangular (35 x 45 cm and 50 x 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 separated by 8.0 m, 4.5 m and 5.4 m, respectively; they are aligned vertically in sections 1, 2, 3, 4 and 5 and separated by 7.8 m. Notice that the largest areas of the grid (8.0 x 7.8 m) are located between sections A and B.

The slab for the basement (floor -1) has a similar layout to the one 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 out of a metal structure.

Alternatives analysed for the concrete flat slabs

Steel-bar-reinforced concrete (original design)

The RC solution consisted of a 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 were assumed in the parking areas.

The reinforcement layout (**Table 4**) consisted of a base reinforcement (BaR) distributed as a 150 x 150 mm grid with a Φ12mm 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%.

Self-compacting steel-fibre-reinforced concrete (constructed solution)

The alternative solution is based on the substitution of the steel rebars with steel macro-fibres, 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 labour and by the preparation and placement of traditional reinforcement. Crimped steel (yield strength of 900 N/mm^2) macro-fibres 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 whilst guaranteeing the same reliability level accepted for RC structures, a post-cracking 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 pre-design and production quality control tests carried out, this mechanical performance can be achieved with 100 kg/m^3 of fibres. However, self-compacting concrete must be used to ensure the workability of material with such a large amount of fibres. Macro-synthetic fibres could also be considered in these applications; however, specific studies on 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 anti-progressive 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, as 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 is grouped into reinforcement for positive moments along the edges of the grid (ER), complementary reinforcement in certain areas (CR), the APC reinforcement and steel fibres (SF).

It should be noted that 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). Since there have been no previous experiences with the use of steel fibres as the primary reinforcement in building-column-supported flat slabs in Spain, the final constructed solution included the APC reinforcement as a precaution.

Therefore, there could be two alternatives based on the use of steel-fibre-reinforced self-compacting concrete (SFRSCC) with 100 kg/m^3 of fibre 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 shown in **Table 6**. The RC concrete mix is the typical mix used in the location proposed by the consulted stakeholders. The differences in the mixes reflect the need to compensate the loss of workability of the fresh concrete due to the addition of fibres. Therefore, changes can be found in the cement, water and aggregate content. The fibres 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 fibres 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 in 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 fibres 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 shown in Equation 3.

$$ORI = \sum_i ORI_i = \sum_i W_i \times E_i \quad (3)$$

Where i is a risk associated with an activity, ORI_i is the Occupational Risk Index of risk i, W_i is the importance of risk i, and E_i is the exposure of the workers to risk i expressed in units of time (hours). W_i 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), as defined in Equation 4.

$$W_i = \frac{P_i \times C_i}{max\{P_i \times C_i\}} = \frac{P_i \times C_i}{1000} \quad (4)$$

For the specific structural typology analysed in this research, three specific risks were evaluated in addition to those presented in Casanovas et al., (2014). These risks were: (1) same-level falls when walking over rebars; (2) structural risk or macro-risk when building conventional slabs; and (3) structural risk or macro-risk when building SFRC slabs. Structural risk or macro-risk is defined in 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 shown 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 it 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 analysed alternatives. The following hypotheses arising from the technical seminars were established:

- It was agreed that steel worker productivity ranges from 200-250 kg/person/hr 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 is 441 hr (RC), 127 hr (SFRSCC+APC) and 66 hr (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, whilst the remaining 40% corresponds to falls through internal hollow spaces in the slabs.
- 3 hr are required to move 18000 kg of bars from the truck to the floor of the building under construction using a crane. 1 extra hour is required for every 18000 kg of bars if they are stockpiled before being lifted.
- 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 one tenth (10%) of the time dedicated to concreting.
- Bars come from a plant located 24.7 km away from the construction site (28 min trip). A truck with a maximum authorised weight limit of 24,000 kg was used. A total of 18000 kg/trip was assumed. Therefore, a total of 6 (RC), 2 (SFRSCC+APC) and 1 (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 analysed are shown in **Table 9**. In view of 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 optimisation of both labour and construction time. The net productivity achieved with the SFRSCC+APC flat slab solution was 17.5 m^2/hr (1 level per week); this entails a 37% reduction in the required time compared to 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 to the RC flat slab solution since fibre reinforcement is less efficient in terms of its ultimate limit state at sectional level than bar reinforcement (placed where the maximum tensile stresses are expected). Nevertheless, it should be noted that numerous full-scale tests on 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 and Pujadas et al., 2012). The latter is based on partial safety factors and material characterisation results from small-scale tests that might not be representative of the real behaviour 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 fibre content optimisation 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 them to have greater energy consumption and CO_2-eq emissions. Furthermore, a rate of 2.4 kg CO_2-eq/kg was considered for the steel fibres, whilst 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 in Hammond and Jones (2011) for world average bars with 39% of recycled steel. SFRSCC also requires 33% more cement than the reference concrete dosage (**Table 6**).
- The SFRSCC alternatives (113 ≤ ORI ≤ 129) are safer than the RC solution (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 (fibres) 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 analysed alternatives had an 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 1/3 of the total number of truck trips and

the time spent occupying public areas). Moreover, it was estimated that 1681 hrs (37 days) were needed to build the concrete slabs for the RC alternative, whilst 1055 hrs (27 days) were needed for the SFRSCC+APC constructed solution and 932 hrs (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, would entail a lower employment generation, which has not been considered in the present analysis.

Satisfaction functions

The last step of the MIVES method consists in defining value functions for each indicator that make it possible to convert dimensional quantities into non-dimensional magnitudes ranging from 0.00 to 1.00 representing satisfaction. The constitutive parameters calibrated for each value function (according to Equation 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 followed 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 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, whilst 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 to 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 an 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. With a view to promoting 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.

It should be noted that 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 analysed 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 yield sustainability indexes between 0.55 (SFRSCC+APC, with BREEAM, 2016) and 0.75 (SFRSCC, DGNB, 2018), with the mean values of I_s ranging from 0.62 (SFRSCC+APC) to 0.69 (RC and SFRSCC). In light of 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. To this end, the environmental requirement should be prioritised in the design and construction phases in order to effectively increase I_s. The use of SFRSCC with recycled aggregates is currently being studied with a view to improving 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 perform quite similarly in terms of sustainability. Therefore, from a decision-making perspective, other additional aspects (e.g. opportunity costs associated with the use of new technologies, the experience of local concrete producers with SFRC mixes, 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 prioritise material technologies and construction alternatives whilst considering the three main pillars of sustainability and minimising subjectivity in the decision-making process.

The method is applied to the real case of an office building in Spain originally designed with reinforced concrete (RC) flat slabs but ultimately constructed with a steel-fibre-reinforced self-compacting concrete (SFRSCC) solution, including an anti-progressive collapse (APC) 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/hr (1 floor per week) was achieved, entailing a 37% reduction in construction time with regard to the latter.
- This reduction in labour hours likewise reduces the exposure time to occupational risks compared to the RC solution. This aspect was included in the MCDM model by means of the occupational risk index (ORI) presented in 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 fibres available today and also by reducing the additional safety measures included in the design of the SFRSCC solutions analysed 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 are assigned to the social requirement, as in the case of DGNB, the performance of the SFRSCC solutions increases 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, 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 MIVES approach, specifically designed to assess the sustainability of slabs. New methods particularly oriented to structural elements or products, as the one presented herein, are very useful to assess the sustainability of new construction technologies prior to their implementation. Moreover, SFRC has had a limited use in structural building slabs and had not been analysed from a sustainability perspective including environmental, social and economic aspects for this particular application.

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, etc. 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 was defined as the total working hours in the construction work, the global sustainability of the fibre-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 fibres are appearing in the market. Their structural contribution is still not clear, but it is a matter of time that these fibres can be used in high structural responsibility applications. The proposed model is also valid to assess the sustainability of alternatives with recycled fibres 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 towards the use of fibre-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 reinforced concrete solution. For fibre-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 multi-criteria 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.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Aitor Maturana, Associate Professor at the University of the Basque Country, for his consent to use data from his research to conduct the present study. They would also like to thank José Hernández for his revision of the occupational risks and Ariadna Moreno from PRECON and the engineers from the companies COPCISA, DRAGADOS and SACYR for sharing data and knowledge on construction processes.

This research was made possible through funding under the SAES project (BIA2016-78742-C2-1-R) of the Spanish Ministry of Economy, Industry and Competitiveness.

REFERENCES

ACI. (2015). *544.6R-15 Report on design and construction of steel fiber-reinforced concrete elevated slabs*. Farmington Hills, United States of America: American Concrete Institute.

Aguado, A., del Caño, A., de la Cruz, M., Gómez, D., and Josa, A. (2012). Sustainability Assessment of Concrete Structures within the Spanish Structural Concrete Code. *Journal of Construction Engineering and Management, 138*(2), 268–276. doi:10.1061/(ASCE)CO.1943-7862.0000419

Akadiri, P.O., Olomolaiye, P.O., and Chinyio, E.A. (2013). Multi-criteria evaluation model for the selection of sustainable materials for building projects. Automation in Construction, 30, 113-125.

Alarcon, B., Aguado, A., Manga, R., and Josa, A. (2011). A Value Function for Assessing Sustainability: Application to Industrial Buildings. *Sustainability, 3*(1), 35-50. doi:10.3390/su3010035

Awadh, O. (2017). Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. *Journal of Building Engineering, 11*, 25-29. doi:10.1016/j.jobe.2017.03.010

AWC. (2015). *Wood Frame Construction Manual for One-and Two-Family Dwellings 2015 edition*. United States of America: American Wood Council. ISBN: 978-1-940383-07-1.

Blanco, A., Cavalaro, S., de la Fuente, A., Grünewald, S., Blom, C.B.M., and Walraven, J.C. (2015a). Application of FRC constitutive models to the modelling of slabs. *Materials and Structures, 48*(9), 2943-2959. doi:10.1617/s11527-014-0369-5

Blanco, A., Pujadas, P., de la Fuente, A., Cavalaro, S.H.P., and Aguado, A. (2015b). Assessment of the fibre orientation factor in SFRC slabs. *Composites Part B: Engineering, 68*, 343-354. doi:10.1016/j.compositesb.2014.09.001

BREEAM. (2016). *BREAM International New Construction 2016. Technical Manual SD233-2.0*. United Kingdom: BRE Global Limited. Retrieved from http://www.breeam.com/BREEAMInt2016SchemeDocument/

Calavera, J. (2003). *Cálculo, construcción, patología y rehabilitación de forjados de edificación: unidireccionales y sin vigas – hormigón, metálicos y mixtos* (5th ed.). Madrid, España: Intemac Ediciones. ISBN: 978-84-88764-14-0

Cartelle, J.J., Lara, M., de la Cruz, M.P., and del Caño, A. (2015). Assessing the global sustainability of different electricity generation systems. *Energy, 89*, 473-489. doi:10.1016/j.energy.2015.05.110

Casanovas, M., Armengou, J., and Ramos, G. (2014). Occupational Risk Index for assessment of risk in construction work by activity. *Journal of Construction Engineering and Management, 140*(1), 1-9. doi:10.1061/(ASCE)CO.1943-7862.0000785, 04013035

Casanovas-Rubio, M., Ahearn, A., Ramos, G., and Popo-Ola, S. (2016). The research–teaching nexus: using a construction teaching event as a research tool. *Innovations in Education and Teaching International, 53*(1), 104-118. doi:10.1080/14703297.2014.943787

Casanovas-Rubio, M. and Armengou, J. (2018). Decision-making tool for the optimal selection of a domestic water-heating system considering economic, environmental and social criteria: Application to Barcelona (Spain). *Renewable and Sustainable Energy Reviews, 91,* 741-753.

Casanovas-Rubio, M., and Ramos, G. (2017). Decision-making tool for the assessment and selection of construction processes based on environmental criteria: Application to precast and cast-in-situ alternatives. *Resources, Conservation and Recycling, 126*, 107-117. doi:10.1016/j.resconrec.2017.07.035

Chiaia, B., Fantilli, A.F., and Vallini, P. (2009). Combining fiber-reinforced concrete with traditional reinforcement in tunnel linings. *Enginering Structures, 31*(7), 1600-1606. doi:10.1016/j.engstruct.2009.02.037

CPH. (2008). Anejo 14 Recomendaciones para la utilización de hormigón con fibras [Annex 14 Recommendations for the use of fibre reinforced concrete]. In *Instrucción de Hormigón Estructural (EHE-08)* [*Spanish Structural Concrete Standard*] (pp. 505-525). Madrid, Spain: Comisión Permanente del Hormigón, Ministerio de Fomento.

de la Fuente, A., Aguado, A., Molins, C., and Armengou, J. (2010). Innovations on components and testing for precast panels to be used in reinforced earth retaining walls. *Construction and Building Materials, 25*(5), 2198–2205. doi:10.1016/j.conbuildmat. 2010.11.003

de la Fuente, A., Armengou, J., Pons, O., and Aguado, A. (2017a). New Precast Concrete Tower System For Wind - Turbine Support Tool To Assess And Its Sustainability Index. *Civil Engineering and Management, 23*(2), 194-203. doi:10.3846/13923730.2015.1023347 de la Fuente, A., Blanco, A., Armengou J, and Aguado A. (2017b). Sustainability based-approach to determine the concrete type and reinforcement configuration of TBM tunnels linings. Case study: extension line to Barcelona Airport T1. *Tunnelling and Underground Space Technology*, 61, 179-188. doi:10.1016/j.tust.2016.10.008

de la Fuente, A., Blanco, A., Pujadas, P., and Aguado, A. (2012b). Experiences in Barcelona with the use of fibres in segmental linings. *Tunnelling and Underground Space Technology, 27*(1), 60-71. doi:10.1016/j.tust.2011.07.001

de la Fuente, A., Campos, R., Figueiredo, A., Molins, C., and Aguado, A. (2012a). A new design method for steel fiber reinforced concrete pipes. *Construction and Building Materials,* 30, 547-555. doi:10.1016/j.conbuildmat.2011.12.015

de la Fuente, A., Escariz, R.C., de Figueiredo, A.D., and Aguado, A. (2013). Design of macro synthetic fibre reinforced concrete pipes. *Construction and Building Materials, 43*, 523-532. doi:10.1016/j.conbuildmat.2013.02.036

de la Fuente, A., Pons, O., Josa, A., and Aguado, A. (2016). Multi-Criteria Decision Making in the sustainability assessment of sewerage pipe systems. *Journal of Cleaner Production, 116*(5), 4762-4770. doi:10.1016/j.jclepro.2015.07.002

del Caño, A., Gómez, D., and de la Cruz, M. (2012). Uncertainty analysis in the sustainable design of concrete structures: A probabilistic method. *Construction and Building Materials, 37*, 865–873. doi:10.1016/j.conbuildmat.2012.04.020

del Caño, A., de la Cruz, P., Gómez, D., and Pérez, M. (2016). Fuzzy method for analysing uncertainity in the sustainable design of concrete structures. *Journal of Civil Engineering and Management, 22*(8): 924-935. doi:10.3846/13923730.2014.928361

Destrée, X. (2004). Structural application of steel fibres as only reinforcing in free suspended elevated slabs: conditions - design - examples. In M. di Prisco, R. Felicetti and G.A. Plizzari (Eds.), *Proceedings pro039: 6th International RILEM Symposium on fibre-reinforced concrete (BEFIB'2004)* (pp. 1073-1082). Varenna, Italy: RILEM Publications SARL.

Destrée, X., and Mandl, J. (2008). Steel fibre only reinforced concrete in free suspended elevated slabs: Case studies, design assisted by testing route, comparison to the latest SFRC standard documents. In Walraven & Stoelhost (Eds.), *Proceedings of the fib Symposium Taylor Made Concrete Structures* (pp. 437-443). London, United Kingdom: Taylor & Francis Group.

DGNB. (2018). Deutsche Gesellschaft für Nachhaltiges Bauen [German Sustainable Building Council] System Version 2018. Retrieved from http://www.dgnb-system.de/en/system/version2018/

Diaz-Sarachaga, J.M., Jato-Espino, D., Alsulami, B., and Castro-Fresno, D. (2016). Evaluation of existing sustainable infrastructure rating systems for their application in developing countries. *Ecological Indicators, 71*, 491-502. doi:10.1016/j.ecolind.2016.07.033

Døssland, Å.L. (2008). *Fibre reinforcement in load carrying concrete structures: laboratory and field investigations compared with theory and finite element analysis* (doctoral dissertation). Norwegian University of Science and Technology, Norway. ISBN 978-82-471-6910-0.

Ellouze, A., Ouezdou, B., and Karray, M.A. (2010). Experimental study of steel fibre reinforced concrete slabs part 1: behaviour under uniformly distributed loads. *International Journal of Concrete Structures and Materials, 4*(2), 113-118.

European Commission. (2016). The European construction sector: a global partner. Retrieved from ec.europa.eu/DocsRoom/documents/15866/attachments/1/translations/en/renditions/native

Falkner, H. (2007). Steel fibre and polymer concrete - basics, model code 2007 and applications. In *Proceedings of an International Conference Evoluzione nella sperimentazione per le costruzione* (pp. 381-400). Cyprus.

fib The International Federation for Structural Concrete (2013). *fib Model Code for concrete structures 2010.* Berlin, Germany: Ernst & Sohn.

Fine, W.T. (1971). Mathematical evaluation for controlling hazards. *Journal of Safety Research, 3*(4), 157-166.

Gödde, L., and Mark, P. (2014). Numerical simulation of the structural behaviour of SFRC slabs with or without rebar and prestressing. *Materials and Structures, 48*(6), 1689-1701. doi:10.1617/s11527-014-0265-z

Gossla, U. (2005). *Development of SFRC free suspended elevated flat slabs, test report*. Aachen, Germany: Aachen University of Applied Science.

Hammond, G., and Jones, C. (2011). *Inventory of Carbon and Energy (ICE), Version 2.0.* Bath, United Kingdom: Department of Mechanical Engineering, University of Bath.

Hedebratt, J., and Silfwerbrand, J. (2014). Full-scale test of a pile supported steel fibre concrete slab. *Materials and Structures 47*, 647-666.

Hosseini, S.M.A., de la Fuente, A., and Pons, O. (2015). Multi-Criteria Decision-Making Method for Assessing the Sustainability of Post-Disaster Temporary Housing Units Technologies: A Case Study in Bam, 2003. *Sustainable Cities and Society, 20,* 38-51. ISSN: 2210-6707.

Hosseini, S.M.A., de la Fuente, A., and Pons, O. (2016). Multicriteria decision-making method for sustainable site location of post-disaster temporary housing in urban areas. *Journal of Construction Engineering and Management, 142*(9). doi:10.1061/(ASCE)CO.1943-7862.0001137

ITAtech. (2016). *ITAtech guidance for precast fibre reinforced concrete segments – Vol. 1: design aspects. ITAtech activity group support. ITAtech report nº7*. Longrine, France: The International Tunnelling and Underground Space Association.

Johansen, K.W. (1962). *Yield-line theory*. London, United Kingdom: Cement and Concrete Association.

John, S., Nebel, B., Perez, N., and Buchanan, A. (2009). *Environmental Impacts of Multi-Storey Buildings Using Different Construction Materials. Research report 2008-02*. Christchurch, New Zealand: University of Canterbury. Retrieved from http://www.nzwood.co.nz/wp-content/uploads/2013/07/Multi-storey_Building_report.pdf

Kind-Barkauskas, F., Kauhsen, B., Polonyi, S., and Brandt, J. (2002). *Concrete Construction Manual*. Munich, Germany: Birkhäuser, Edition Detail.

Liao, L., de la Fuente, A., Cavalaro, S., and Aguado, A. (2015a). Design of FRC tunnel segments ductility considering the requirements of the MC 2010. *Tunnelling and Underground Space Technology, 47*(3), 200-210. doi:10.1016/j.tust.2015.01.006

Liao, L., de la Fuente, A., Cavalaro, S., and Aguado, G. Carbonari. (2015b). Experimental and analytical study of concrete blocks subjected to loads concentrated with an application to TBM-constructed tunnels. *Tunnelling and Underground Space Technology, 49*(1), 295-306. doi:10.1016/j.tust.2015.04.020

Macías, M. and García Navarro, J. (2010). Metodología y herramienta VERDE para la evaluación de la sostenibilidad en edificios [VERDE, a methodology and tool for a sustainable building assessment]. Informes de la Construcción, 62(517), 87-100.

Maturana, A. (2013). *Estudio teórico-experimental de la aplicabilidad del hormigón reforzado con fibras de acero a losas de forjado multidireccionales* (doctoral dissertation). Universidad del País Vasco, Spain.

Maturana, A., Sanchez, R., Canales, J., Orbe, A., Ansola, R., and Veguería, E. (2010). Technical economic analysis of steel fibre reinforced concrete flat slabs. In *Proceedings of XXXVII IAHS World Congress on Housing*.

Maturana, A., Canales, J., Orbe, A., and Cuadrado, J. (2014). Análisis plástico y ensayos de losas multidireccionales de HRFA [Plastic Analysis and Testing of multidirectional SFRC flag slabs]. *Informes de la Construcción, 66*(535). doi:10.3989/ic.13.021

Meda, A., Plizzari, G.A., and Riva, P. (2004) Fracture Behaviour of SFRC slabs on grade. *Materials and Structures, 37*(6), 405-411. doi:10.1007/BF02479637

Meda, A., and Rinaldi, Z. (2014). Steel reinforcement fibers for precast lining in tunnels with different diameters. In *FRC 2014 Joint ACI-fib International Workshop. Fibre Reinforced Concrete Applications. July 24-25* (pp. 522-531). Montreal, Canada.

Mitchell, D., and Cook, W.D. (1984). Preventing Progressive Collapse of Slab Structures. *Journal of Structuctural Engineering, 110*(7), 1513–1532.

Michels, J., Waldmann, D., Mass S., and Zürbes, A. (2012). Steel fibers as only reinforcement for flat slab construction – Experimental investigation and design. *Construction and Building Materials, 26*, 145-155.

Ormazabal, G., Viñolas, B., and Aguado, A. (2008). Enhancing Value in Crucial Decisions: Line 9 of the Barcelona Subway, *Journal of Management in Engineering, 24*(4), 265–272. doi:10.1061/(ASCE)0742-597X(2008)

Ortiz, J.A., de la Fuente, A., Mena-Sebastià, F., Segura, I., and Aguado, A. (2017). Steel-fibre-reinforced self-compacting concrete with 100% recycled mixed aggregates suitable for structural applications. *Construction and Building Materials, 156*, 230-241. doi:10.1016/j.conbuildmat.2017.08.188

Öšlejs, J. (2008). New frontiers for Steel fiber-reinforced concrete: Experience from the Baltics and Scandinavia. *Concrete International, May 2008*, 45-50.

Pardo, F., and Aguado, A. (2014). Investment Priorities for the management of hydraulic structures. *Structre and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 11*(10), 1338-1351. doi:10.1080/15732479.2014.964267

Politi, S., and Antonini, E. (2017). An expeditious method for comparing sustainable rating systems for residential buildings. *Energy Procedia, 111*, 41-50.

Pons, O. (2009). *Arquitectura escolar prefabricada a Catalunya* [*Prefabricated school buildings in Catalonia*] (Doctoral dissertation). Universitat Politècnica de Catalunya, Spain. Retrieved from http://hdl.handle.net/10803/6133

Pons, O., and Aguado, A. (2012). Integrated model for sustainable value assessment applied to technologies used to build schools in Catalonia, Spain. *Building and Environment, 53*, 49-58. doi:10.1016/j.buildenv.2012.01.007

Pons, O., and de la Fuente, A. (2013). Integrated sustainability assessment method applied to structural concrete columns. *Construction and Building Materials, 49*, 882–893. doi:10.1016/j.conbuildmat.2013.09.009

Pons, O., de la Fuente, A., and Aguado, A. (2016). The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications. *Sustainability, 8*(5),1-15. doi:10.3390/su8050460

Pujadas, P., Blanco, A., Cavalaro, S.H.P., Aguado, A., Grunewald, S., Blom, K., and Walraven, J. (2014). Plastic fibers as the only reinforcement for flat slabs suspended: parametric study and design considerations. *Construction and Building Materials, 70*, 88-96. doi:10.1016/j.conbuildmat.2014.07.091

Pujadas, P., Blanco, A., Cavalaro, S.H.P., de la Fuente, A., and Aguado, A. (2017). The need to consider flexural post-cracking creep behavior of macro-synthetic fiber reinforced concrete. *Construction and Building Materials, 149*, 790-800. doi:10.1016/j.conbuildmat.2017.05.166

Pujadas, P., Blanco, A., de la Fuente, A., and Aguado, A. (2012). Cracking behaviour of FRC slabs with traditional reinforcement. *Materials and Structures, 45*(5), 707-725. doi:10.1617/s11527-011-9791-0

Regalado, F. (1999). *Los forjados de los edificios: pasado, presente y futuro*. Alicante, Spain: Cype ingenieros.

Reyes, J.P., San-Jose, J.T., Cuadrado, J., and Sancibrian, R. (2014). Health & Safety Criteria for Determining the value of sustainable construction projects. *Safety Science, 62*, 221-232. doi:10.1016/j.ssci.2013.08.023

Saaty, T.L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research, 48*(1), 9-26. doi:10.1016/0377-2217(90)90057-I

San-Jose, J.T., and Cuadrado J. (2010). Industrial building design stage based on a system approach to their environmental sustainability. *Construction and Building Materials, 24*(4), 438–447. doi:10.1016/j.conbuildmat.2009.10.019

San-Jose, J.T., and Garrucho, I. (2010). A system approach to the environmental analysis industry of buildings. *Building and Environment, 45*(3), 673–683. doi:10.1016/j.buildenv.2009.08.012

Salehian, H., and Barros, J.A.O. (2015). Assessment of the performance of steel fibre reinforced self-compacting concrete elevated slabs. *Cement & Concrete Composites, 55*, 268-280.

SDI. C-2017 (2017). Standard for Composite Steel Floor Deck-Slabs. American National Standards Institute/Steel Deck Institute.

Terracciano, G., Di Lorenzo, G., Formisiano, A., and Landolfo, R. (2015). Cold-formed thin-walled steel structures as vertical addition and energetic retrofitting systems of existing masonry buildings. European Journal of Environmental and Civil Engineering, 19(7), 850-866.

UN General Assembly. (2005). *2005 World Summit Outcome: resolution/adopted by the General Assembly*, 24 October 2005, A/RES/60/1. Retreived from http://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_60_1.pdf

USGBC (n.d.). LEED Leadership in Energy and Environmental Design. United States. Green Building Council. Retrieved from http://www.usgbc.org/leed

USGBC. (2015*). LEED V4 for Building Design and Construction: New Construction.* U.S. Green Building Council. Retrieved from http://greenguard.org/uploads/images/LEEDv4forBuildingDesignandConstructionBallotVersion.pdf

Villegas, N., de los Ríos, B., and Aguado, A. (2010). Value rate in highway cross-sections during its life cycle*. International Review of Civil Engineering, 1*(1), 100-109.

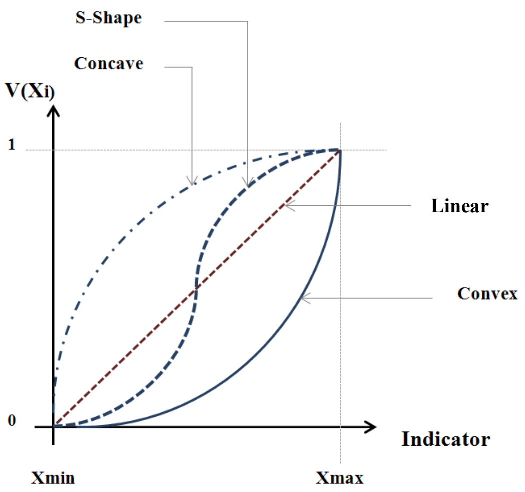
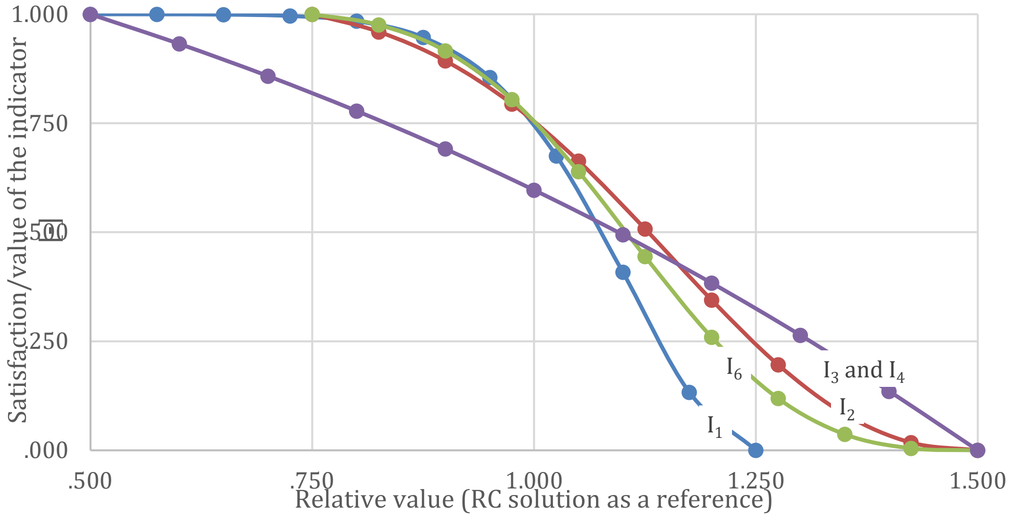


Fig. 1. Value function shapes



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

Table 1. Experimental research programmes on steel-fibre-reinforced concrete flat slabs and real buildings constructed using this technology

Author	Type	Country	Max. span (m)	Rebars	C_f (kg/m^3)	λ_f/l_f-Type
Falkner, 2007; Hedebratt and Silfwerbrand, 2014	FSLT	Germany	5.00·5.00·0.15	Yes	40	80/60-HE
Hedebratt and Silfwerbrand, 2014; Døssland, 2008	FSFT	Norway	3.00·7.00·0.15	None/Yes	62	65/60-HE
Hedebratt and Silfwerbrand, 2014; Gossla, 2005; Destrée and Mandl, 2008	FSFT	Luxembourg	6.00·6.00·0.20	Yes	100	39/50-C
Destrée and Mandl, 2008	FSFT	Estonia	5.00·5.00·0.18		100	
Destrée and Mandl, 2008	FSFT	Belgium Australia	3.10·3.10·0.16	None	45 45	54/35-TCE
Hedebratt and Silfwerbrand, 2014;	RB	Latvia	6.00·6.00·0.25		100	39/50-C
Destrée and Mandl, 2008	RB	Estonia	-	Yes	100	39/50-C
Hedebratt and Silfwerbrand, 2014; Öšlejs, 2008	RB	Latvia	4.00·4.00·0.16	-	100	39/50-C
Maturana, 2013	RB	Spain	8.00·7.60·0.30	Yes	100	39/50-C
Michels et al., 2012	SST	Switzerland	2.34Φ0.20	None	100	39/50-C
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	Yes	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 fibres (steel); l_f: length of the fibre; λ_f: aspect ratio of the fibre (length/diameter of the fibre).

Table 2. Requirement tree for the sustainability analysis of concrete slabs

Requirement	Criteria	Indicator	Unit
R_1 Economic (λ_{R1} = 21-33%)	C_1 Construction costs (λ_{C1} = 100%)	I_1 Total cost (λ_{I1} = 100%)	k€/m^3
R_2 Environmental (λ_{R2} = 33-60%)	C_2 Resource consumption (λ_{C2} = 33%)	I_2 Steel consumption (λ_{I2} = 33%)	kg/m^3
		I_3 Energy consumption (λ_{I3} = 67%)	MJ/m^3
	C_3 Emissions (λ_{C3} = 67%)	I_4 CO_2-eq emissions (λ_{I4} = 100%)	Kg/m^3
R_3 Social (λ_{R3} = 24-33%)	C_4 Occupational risks during construction (λ_{C4} = 80%)	I_5 ORI (λ_{I5} = 100%)	Weighted hour
	C_5 Third-party effects (λ_{C5} = 20%)	I_6 Noise pollution (λ_{I6} = 70%)	dB
		I_7 Other inconveniences (λ_{I7} = 30%)	Attribute

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 of this paper redistributed these weights to the three main pillars in order to apply the requirement tree of Table 2.

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

Reinforcement	Ground floor	Floor 1	Floor 2	Floor 3	Roof floor
BaR	19565 kg	14550 kg	14550 kg	14550 kg	14550 kg
BR	1366 kg	210 kg	210 kg	210 kg	1125 kg
TR	3479 kg	2075 kg	2075 kg	2075 kg	2733 kg
PR	2820 kg	2456 kg	2456 kg	2456 kg	2456 kg
RR	781 kg	781 kg	781 kg	781 kg	781 kg
Amount (kg/m^3)	**111 kg/m^3**	**107 kg/m^3**	**107 kg/m^3**	**107 kg/m^3**	**117 kg/m^3**

Table 5. Amounts of reinforcement for the SFRC flat slab alternatives

Reinforcement	Ground floor	Floor 1	Floor 2	Floor 3	Roof floor
ER	512 kg	1025 kg	1025 kg	1025 kg	2131 kg
CR	2233 kg	1930 kg	2058 kg	1832 kg	2674 kg
APC	3103 kg	2627 kg	2627 kg	2627 kg	4378 kg
Amount (kg/m^3)	**23 kg/m^3**	**29 kg/m^3**	**29 kg/m^3**	**29 kg/m^3**	**49 kg/m^3**
SF	100 kg/m^3	100 kg/m^3	100 kg/m^3	100 kg/m^3	100 kg/m^3
Total amount (kg/m^3)	**123 kg/m^3**	**129 kg/m^3**	**129 kg/m^3**	**129 kg/m^3**	**149 kg/m^3**

Note: ER: reinforcement for positive moments along the edges of the grid; CR: complementary reinforcement in certain areas; APC: anti-progressive collapse reinforcement; SF: steel fibres.

Table 6. Concrete mixes for the RC and the SFRSCC alternatives

Components	Characteristics	RC	SFRSCC
Cement (kg/m^3)	CEM I	300	-
	CEM II/BM-VLS 42.5R	-	400
Aggregates (kg/m^3)	-	1905	1850
Water (kg/m^3)	-	165	185
w/c (-)	-	0.55	0.41
Additions (kg/m^3)	Fly ash	-	120
Fibres (kg/m^3)	Steel	-	100
Admixture (l/m^3)	Superplasticiser	1.6	4.6

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

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

Table 8. ORI results for each alternative analysed

Risk - Activity	W (dimensionless)	Exposure (E) time (hours)			$W \times E$ (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 macro-risk: RC slabs	0.038	1,681.2	-	-	63.886	-	-
Structural risk or macro-risk: SFRSCC slabs	0.050	-	1,054.5	932	-	52.723	46.578
ORI					**190**	**129**	**113**

Table 9. Indicator results obtained for each of the analysed flat slab alternatives

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	

Table 10. Values obtained for each of the analysed flat slab alternatives

Rating criteria	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
μ_{Is}	0.69	0.62	0.69
cv_{Is}	0.44%	11.36%	8.06%

Note 1: μ_{Is}: mean; cv_{Is}: covariance

Note 2: The authors of this paper 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.