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A NEW BREED OF SUSTAINABLE ULTRA-LIGHTWEIGHT AND ULTRA-SHALLOW STEEL-CONCRETE COMPOSITE FLOORING SYSTEM: LIFE CYCLE ASSESSMENT OF MATERIALS

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Abstract. *Ssustainability and the reduction of CO_2 emission have taken an important attention in all industries. In particular, the construction industry is influenced due to the extensive use of materials and the large amount of waste generated. An enormous contribution to sustainable design can be made by changing the design of traditional members and systems and integrating new or under-developed materials from the initial stages. The aim of this study is to present a new composite flooring system which exercises the sustainability approach in the selection of its components. A comprehensive evaluation of the new ultra-light and ultra-shallow flooring system through Life Cycle Assessment (LCA) is conducted. The evaluation is performed based on three stages (i.e., production stage, transportation and end of life stage).*

1 INTRODUCTION

In recent years, assessing and controlling carbon emissions have become a basic strategy to achieve sustainable developments. The European Community and 37 industrialised countries committed to reduce greenhouse gases (GHG) emissions by 18% lower than the 1990's level from 2013 to 2020 [1]. The sustainability issue has taken an important attention in all industries. In particular, the construction industry is influenced by the higher use of materials and the larger amount of waste [2]. Buildings are significant contributors to carbon emissions, not only caused by the energy consumptions in building maintenance and operation, but also due to the substantial material use and intensive onsite construction operations. It has been stated that buildings account for 40% from the global material flow [1]. Concrete is an essential reported construction material with the global annual consumption of 1 ton per capita. Concrete has been identified as a carbon intensive material, and cement being the key component of concrete is responsible for 5–7% of the world's carbon emissions [3]. The on-site construction process is another source of carbon emission, mostly contributed from fuel consumption in material transportation and heavy equipment, waste treatment management and embodied carbon in temporary materials [1]. Prefabrication is a sustainable construction process of enhanced quality control, environmental performance, and site safety, as well as responsible for the reduction of labour work and construction time [3]. The use of pre-casting techniques can reduce the waste up to 52% and reduce the timber formwork up to 70% [4].

Energy behaviour for different building materials have been examined illustrating the importance of using natural and recycled building materials because of their low level of consumed energy, when the quality requirements allow it [5]. Energy in the building can be classified into two types: (i) energy for serving/maintenance for the building through its beneficial time, and (ii) energy that drives into production of the construction (embodied energy) using different building materials [6]. Embodied energy of buildings can change over a wide range of limits depending on the selection of building materials and structural systems. The common traditional systems composing the main structure of buildings are RC slabs, Steel frames, RC frames, concrete block masonry, burned clay brick masonry and tiled roofs [6] and steel roof cladding. Alternative building technologies such as prefabricated roofing systems, mud blocks, filler slab roof, masonry vaults and lime-pozzolana cements can be used for reducing the embodied energy of the buildings. Embodied energy can be further divided into: (i) energy used in the manufacture of the basic building materials, (ii) energy consumed for transportation of the building materials, and (iii) energy needed for assembling the different materials to form the building at the end.

In this regard this paper's contribution focuses on presenting a life cycle assessment of new prefabricated lightweight floor system which is characterised by using lightweight materials and integrating thin-walled steel beams into the floor with the advantages of low construction height as well as quick erection due to the prefabrication process.

2 SUSTAINABILITY OF MODERN SHALLOW FLOOR CONSTRUCTION

2.1 MODERN FLOOR SYSTEM TRENDS

Sustainability is not merely related to the environmental nature such as climate changes, wastes (landfill), materials' consumption, energy consumption and recycling. But it is also related and assessed based on the economic aspects such as life cycle costs, maintenance, value conservation, flexibility, functionality and reusability, as well as the social demands such as comfort, health and safety, aesthetics and urban redevelopment.

Consequently, sustainable floors require to fulfill the ecological, economical and social sustainability demands [7]. Moreover, a floor should be designed for today customer requests particularly vibration comfort, sound and heat insulation in addition to other structural design requirements. However, a floor should be economical and cost-effective in the construction stage due to rapid erection and availability in short delivery time. The high degree of prefabrication ensures the increase in safety on the construction site during erection and in the final stage due to the quality control in the shop.

In addition, modern floor design should take into account future use. As the designers are normally not capable to predict the future, the floor design and construction should be flexible easily adaptable to customer anticipations, with the potential of reuse, thus the investment itself will become sustainable. Also, maintenance and alterations of installation services must be feasible and as easy as possible [8].

These additional requirements demand the design of large spans with reduced number of columns in combination with shallow lightweight flooring systems which overcome limitations regarding service installation. In the following section, the recently developed state-of-the-art USFB, CoSFB, Cofradal and a new ultra-light ultra-shallow flooring system are presented to fulfill the above described criteria.

2.2 STATE-OF-THE-ART IN SHALLOW FLOOR CONSTRUCTION AND A NEW PROPOSAL

Shallow-floor construction is characterized by integrating the steel beam into the slab's thickness. The steel section consists from a hot rolled beam with a welded plate underneath it to provide the bearing for incoming slabs. The width of the welded plate is larger than the bottom flange of the hot rolled section, hence the slab elements can be easily placed [9]. The shallow-floor beam (SFB) can be incorporated with any type of slab. Prefabricated or partially prefabricated concrete slabs can fit perfectly with the SFB; a quick and safe erection is assured. By using this type of construction systems the structural depth of the floor is reduced and thus the overall height of the building is effectively reduced while the total number of floors can be increased within the predefined allowed building envelop. Mechanical and Electrical (M&E) services such as cooling and heating devices are quickly installed due to the absence of down stand steel beams. However, due to the small beam height, the design of the SFB is governed by the stiffness of the system and hence spans are limited.

A good example of slim-floor construction is the Ultra-Shallow Flooring Beam (USFB), which consists from perforated steel beams designed to connect with floor slabs placed within the steel flanges (i.e., plug composite) in order to reduce the structural depth of the composite sections [10]. These composite structures also have other advantages for example increased load carrying capacity, fire resistance [11], local buckling stiffness and a significant increase in the bending stiffness when compared with the original steel beams. Furthermore, the construction cost is reduced by eliminating the construction time and the amount of formwork needed [10]. Common applications for USFBs have been based on slabs with depths ranging from 180 to 300 mm in which the concrete is placed level with the top flange. The practical span to depth ratio of USFBs is usually in the range of 25 to 30. Consequently, the USFB is limited to a span up to 9m with a depth up to 300 mm and that may lead to an uneconomical solution.

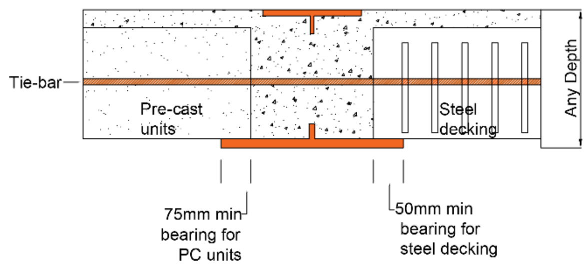


Figure 1: Schematic of USFBs with tie- bar shear connector [10]

Another recently developed shallow and lightweight flooring system is the Composite Slim Floor Beam (CoSFB) which has been based on the development of an advanced composite connection by using concrete dowels. The resulting structural solution allows for the possibility to achieve a slim-floor beam span up to 12m with a slim-floor beam centre of 10m and an overall depth of only 350 mm with propping used during construction phase [12]. This flooring system has been used with the Cofradal260 slab (composite floor slab) which consists from a cold-rolled metal deck, a thermal insulation layer and a concrete layer. The CoSFB construction in the site involves further work to complete the construction, such as placing the concrete on site, even when Cofradal slab is used, because it is not a fully prefabricated flooring system, thus the energy consumption, CO_2 emissions, construction cost and potential site repair and maintenance costs are still high.

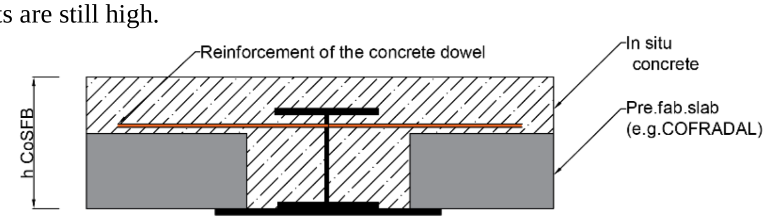


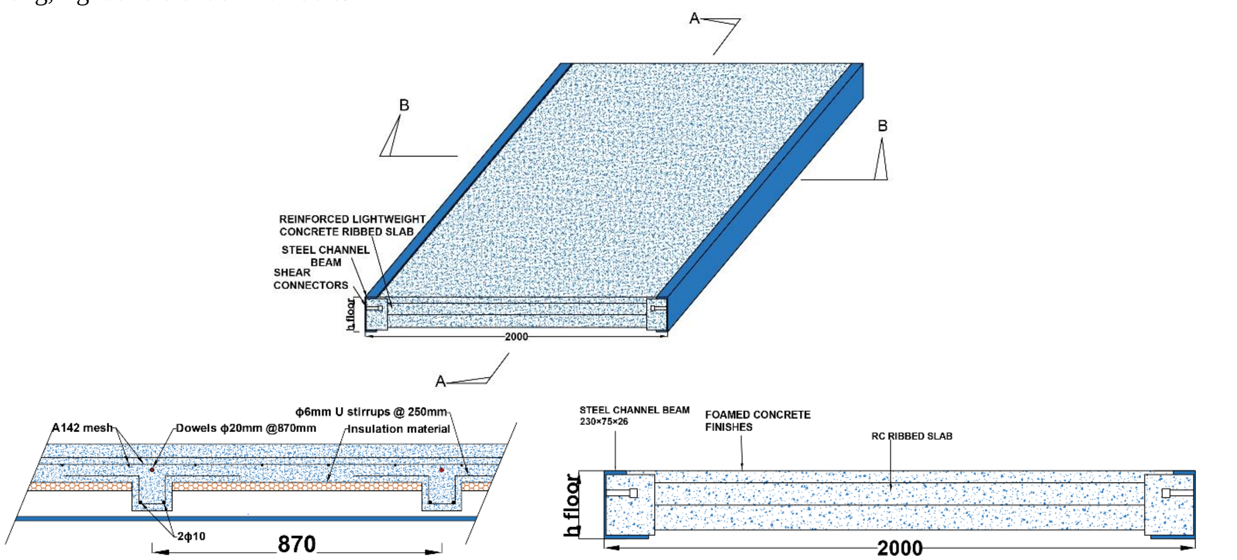
Figure2: Typical CoSFB section [12]

Consequently, a new ultra-light and ultra-shallow flooring system is presented herein which is developed along with the methodology of Life Cycle Assessment (LCA) in terms of the selection of its materials (i.e., lightweight concrete and lightweight steel) while the benefits of factory full-prefabrication are exploited. The authors were also focused on producing a flooring system with a span that exceeds the current span and depth limitations comparing with other existing systems as it is shown in Figure 3 in an attempt to push the boundaries, understand the system behavior and develop the technology.

The potential benefits of the new flooring system is the reduced number of erection/installation lifts by using lighter materials (concrete and steel) and wider units, while reducing site operations and benefitting from full offsite fabrication. This proves an effective approach when considering the material cost against the fabrication and site erection costs being proportionally in the order of 35% and 65%, respectively. In addition, the proposed prefabricated product reduces the site labour works and the overall construction cost. The increase in speed of site construction, reduced site work and lighter construction along with larger spans is anticipated to be of great benefit to the construction industry.

Furthermore, the current trend in the industry is to reduce the amount of energy consumption, CO_2 emissions and cost by using prefabricated lightweight materials. These prefabricated elements not only will be produced with a quality assured method of the shop fabrication but will also reduce the potential site repair and maintenance costs by eliminating the onsite mistakes due to bad workmanship.

The new ultra-light and ultra-shallow proposed flooring system leads to a flexible and economic construction which further fulfils the requirements for sustainable structures with the efficient use of raw material in combination with long, light and slender members.



Sec (A-A) Sec (B-B)

Figure 3: New ultra-light shallow flooring

3 LIFE CYCLE ASSESSMENT (LCA)

3.1 GENERAL

LCA is a method widely used to estimate the ecological impact of processes, products, and designs over the whole life cycle [13]. In the LCA it is very significant to compare some possible substitute solutions which have the same required performance but differ regarding environmental consequences. Since 1960s LCA has been applied to several scenarios with different degree of success, from minor industrial products, for example the study by Teasley for Coca-Cola Company, to major and more complicated systems, for instance the cities and national economies [14]. In recent years various labelling systems have been developed for the interpretation of the LCA results for buildings in terms of environmental or even sustainable quality [15]. They specify ratings based on the evaluation of different specifications regarding the environmental performance of the buildings. The internal benefits from an ecological assessment assures the detection of strategic risks and environmental concerns, the development of sustainable products based on ecological information (Eco-design), and the communication with authorities, councils and decision-makers. While, the external benefits are the improvement of the overall functional and structural performance due to environmental considerations, the support of ecological innovations, and the decrease of ecological impacts in addition to the competitive advantage by including the environmental aspects. Generally, the investor considers the life cycle assessment of his buildings to assure the sustainability and durability of design and investment stability.

Most countries were motivated by the first oil-crisis in 1973 to implement building codes for insulation standards which result in an enormous saving of energy for operation (heating and cooling) and domestic services. Technological development in sealing methods and HVAC-systems has decreased the buildings' operational energy consumptions to very low levels up to the extend known as passive-house projects [9]. These changes have induced the importance of expanding the domain of energy saving from the exclusive focus on operational energy in the use phase to the inclusion of processing energy such as energy for mining, processing, transportation, assembly and construction site operations.

This paper is focused on the reduction of embodied energy and embodied carbon. For practical purposes a typical floor layout is used and the LCA functional unit for evaluating the new flooring systems has been identified based on the adopted floor layout. The floor layout grid is assumed to cover a typical grid layout requested by the industry of today [9].

3.2 METHOD OF STUDY

In this study the life-cycle assessment of materials used in the new ultra-light shallow flooring system and CoSFB with Cofradal 260mm are presented and it considers the demolition and recycling of the building materials. It focuses on two impact categories only: (a) embodied carbon and (b) embodied energy impacts. LCA has been applied to calculate the embodied energy and embodied carbon of the flooring systems for grid 8.10m×8.10m. The LCA study is conducted at three stages: (i) the influence of the materials used in the production of the flooring systems, (ii) the influence of the transportation of these materials, and (iii) the end of life of the materials of flooring systems themselves.

3.3 LIFE CYCLE INVENTORIES USED FOR THE ASSESSMENT

For the LCA, Life Cycle Inventories (LCI) are required to provide information on the materials and energy flows during their entire life. The collection of data is a critical stage in LCA designing. However, an ideal LCA should be established entirely on soliciting and site-specific data. Such data requires a large amount of time and effort [1]. LCA is popular due to its efficiency by employing well-established databases. The incorporation of the site-specific data and existing databases is generally unavoidable in LCA investigation. This study adopts one type of data depending on one widely referenced embodied energy coefficient databases which is the Inventory of Carbon and Energy databases [16]. The quantities of the materials used in the new ultra-light shallow flooring system, and the CoSFB/Cofradal solution is determined and multiplied by their particular embodied energy and embodied carbon coefficients. The sum of these results, including the embodied energy from the waste materials which assumed as (7%) of total amounts, gives the total embodied energy for the flooring system. In addition, the amounts of these materials including waste are multiplied by the embodied carbon and embodied energy coefficients for the transportation method of 0.15 kg CO_2e/km-tonne and 2.4 MJ/km-tonne respectively (typical fully-loaded heavy haulage vehicle which assumed one-way journey as it will move from one job to another instead of return empty) and they are also multiplied by the transportation distance which is taken as (100km) according to an ICE inventory [16]. In addition, the end-of-life scenario for steel has been used suggesting the full benefits of recycling at the end of life [16]:

− 95% recovery rate for structural steel while 5% is lost and goes to landfill.

− Re-bars are separated from the concrete; it is assumed, that 75% of the sorted re-bars are recycled and 25% lost and goes to landfill.

− For concrete, it has been only considered at the demolition stage [17] because no information has been provided by the ICE inventory [16] about the demolition and recycling method.

The embodied carbon and embodied energy coefficients of materials used in the calculations of LCA of the flooring system are detailed in Table 1. The embodied carbon and embodied energy coefficients for steel and concrete for the end of life scenario are shown in Table 2.

Material	Embodied Energy Coefficient (MJ/kg)	Embodied Carbon Coefficient (MJ/kg)
Cement	5.5	0.93
Sand	0.081	0.0048
Gravel	0.083	0.0052
Water	0.01	0.001
Fly ash	0.1	0.008
Silica fume	0.1	0.014
Super-plasticizer	9.0	0.25
Reinforcing steel bar	17.4	1.31
Metal Deck	22.6	1.54
Steel Section	21.50	1.42
Rock wool Insulation	16.8	1.12
Expanded Polystyrene	88.6	3.29

Table 1: Embodied carbon and embodied energy coefficients for the production of materials [16]

Material	Embodied Energy Coefficient (MJ/kg)	Embodied Carbon Coefficient (MJ/kg)
Steel recycling	13.1	0.75
Reinforcing steel bar recycling	11	0.74
Concrete demolition	0.007 [17]	0.00054 [17]
Rock wool Insulation	N.D.A	N.D.A
Expanded Polystyrene	N.D.A	N.D.A

Table 2: Embodied carbon and embodied energy coefficients for the end of life of materials [16] and [17]

4 LCA OF FLOORING SYSTEMS

4.1 BACKGROUND THEORY

The structural performance of the new ultra-light shallow flooring system has been proven analytically using the stress block method as shown in Figure 5 in addition to the structural performance of the CoSFB flooring system which has been also verified using the manufacturer software [9]. Furthermore, the overall flexibility realises the requested demands on economic and social sustainability. The LCA functional unit for evaluating the new ultra-light shallow flooring system and CoSFB with Cofradal 260mm has been defined based on a grid of 8.1m x 8.1m (see section 4.2). The grid is designed as such to cover the standard grid requested by today's market.

The embodied carbon and embodied energy evaluations considered in this study include the following phases: production of materials, transportation and end of life. The embodied energy and embodied carbon evaluations procedure for the flooring systems are summarised below.

1) Production phase includes the materials of each concrete mix used for every flooring system and steel sections that provide an area of (8.10m×8.10m). Hence, the embodied energy EE_P and EC-P, in the production phase can be calculated using the following equations [18]:

$$EE_{-P} = \sum_{i=1}^{n} \left(W_i \times EE_{(i)-LCI}\right) \qquad (1)$$

$$EC_{-P} = \sum_{i=1}^{n} \left(W_i \times EC_{(i)-LCI}\right) \qquad (2)$$

Where i represents a raw material constituting the flooring system, n is the number of raw materials added for each flooring system production, and Wi, EE_{i_LCI} and EC_{i_LCI} are the unit weight (kg), embodied energy inventory (MJ/kg), and embodied carbon inventory (kgCO_2e/kg) of raw material i, respectively.

2) Transportation phase includes the transportation of the materials and prefabricated units to the building site applicable to each solution. The transportation distance is assumed to be (100km) according to the ICE inventory [16]. Overall, the embodied energy and embodied carbon from the transportation phase can be obtained from:

$$EE_{-T} = \sum_{i=1}^{n} \left(W_i \times D_i \times EE_{(i)-LCI(TR)}\right) \qquad (3)$$

$$EE_{-T} = \sum_{i=1}^{n} \left(W_i \times D_i \times EC_{(i)-LCI(TR)}\right) \qquad (4)$$

Where Wi is the unit weight (tonne), Di is the transportation distance of each flooring system constituent material i from the manufacturing plant to the building site (km), $EE_{(i)\text{-}LCI(TR)}$ is the embodied energy inventory related to the heavy haulage vehicle (MJ/km.tonne). $EC_{(i)\text{-}LCI(TR)}$ is the embodied carbon inventory related to the heavy haulage vehicle (kgCO_2e/km.tonne).

3) End of life phase includes the steel recycling and transportation of recycled steel and concrete demolition and transportation of crushed concrete. The transportation distance is assumed as (100km) according to the ICE inventory [16]. The embodied energy from the end of life phase of steel can be obtained from:

$$EE_{-ST-EOL} = \sum_{i=1}^{n} \left(W_i \times RC \times EE_{(i)-LCI}\right) + \sum_{i=1}^{n} \left(W_i \times D_i \times EE_{(i)-LCI(TR)}\right) \qquad (5)$$

$$EE_{-ST-EOL} = \sum_{i=1}^{n} \left(W_i \times RC \times EC_{(i)-LCI}\right) + \sum_{i=1}^{n} \left(W_i \times D_i \times EC_{(i)-LCI(TR)}\right) \qquad (6)$$

Where Wi is unit weight of (kg), RC is the recycling content of re-bars and steel sections, $EE_{(i)\text{-}LCI(R)}$ is the embodied energy inventory (MJ/kg), $EC_{(i)\text{-}LCI(R)}$ is the embodied carbon inventory for the recycling of steel material. Wi is unit weight (tonne), Di is the transportation distance of recycled material i from the construction site to the recycling plant (km), $EE_{(i)\text{-}LCI(TR)}$ is the embodied energy inventory and $EC_{(i)\text{-}LCI(TR)}$ is the embodied carbon inventory related to the heavy haulage vehicle (kgCO_2e/km.tonne). The embodied energy from the end of life phase of concrete can be obtained from:

$$EE_{-CON-EOL} = \sum_{i=1}^{n}\left(W_i \times EE_{(i)-LCI}\right) + \sum_{i=1}^{n}\left(W_i \times D_i \times EE_{(i)-LCI(TR)}\right) \quad (7)$$

$$EE_{-CON-EOL} = \sum_{i=1}^{n}\left(W_i \times EC_{(i)-LCI}\right) + \sum_{i=1}^{n}\left(W_i \times D_i \times EC_{(i)-LCI(TR)}\right) \quad (8)$$

Where Wi is unit weight of (kg), $EE_{(i)\text{-}LCI(R)}$ is the embodied energy inventory (MJ/kg), and $EC_{(i)\text{-}LCI(R)}$ is the embodied carbon inventory ($kgCO_2e/kg$) for the demolition of concrete. Wi is the unit weight (tonne), Di is the transportation distance of demolished material i from the construction site to the landfill (km), $EE_{(i)\text{-}LCI(TR)}$ is the embodied energy inventory related to the heavy haulage vehicle ($kgCO_2e/km.tonne$).

4.2 LCA OF GRID 8.10M× 8.10M

To evaluate the environmental performance of the new flooring system, the embodied carbon and embodied energy for a typical 8.10m x 8.10m grid (functional unit) are calculated and presented in Table 3. The most important design results are (L = Beam Span = 8.10m; a = Beam Distance = 8.10m; Dead Load of slab = 2.8 kN/m^2; Additional DL= 1.7 kN/m^2; LL = Live Load= 2.50 kN/m^2; Partition wall =1.00 kN/m^2). The layout of the flooring system shown in Figure 4.

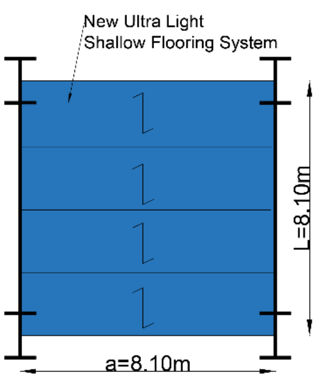


Figure 4: Grid 8.10m ×8.10m

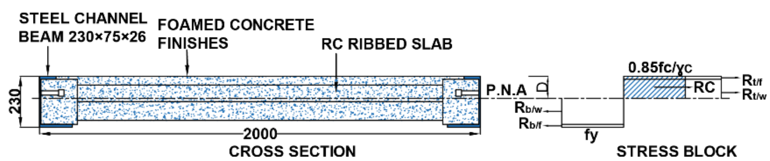


Figure 5: New ultra-light ultra-shallow flooring system section

Stage	Embodied Energy (GJ)	Embodied Carbon (tonne CO_2 e)
Production	90.19	8.67
Transport	3.01	0.19
End of Life	36.54	2.12

Table 3: Embodied Carbon and Embodied Energy for the new proposed flooring system

In addition, the environmental performance of the CoSFB with Cofradal 260mm, the embodied carbon and embodied energy for the same grid are calculated according to the previous procedure and presented in Table 4. The most important design results are (L= Beam Span = 8.10m; a = Beam Distance = 8.10m; Dead Load of slab = 2.80 kN/m^2; Additional DL= 1.7 kN/m^2; LL = Live Load= 2.5 kN/m^2; Partition wall =1.00 kN/m^2) [9]. Figure 6 and 7 shown the layout and the cross-section of CoSFB system.

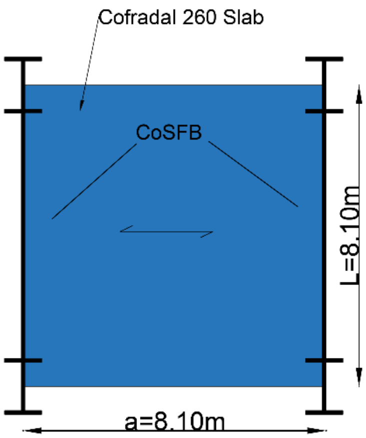


Figure 6: Grid 8.10m×8.10m

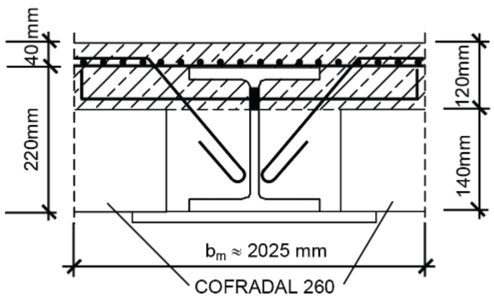


Figure 7: CoSFB Section,
HE220B, S355M + Plate 400x20, S355, In situ concrete C30/37 [9]

Stage	Embodied Energy (GJ)	Embodied Carbon (tonne CO_2 e)
Production	106.25	8.69
Transport	5.24	0.32
End of Life	46.63	3.10

CONCLUSION

The construction sector is responsible for around 50% of the resource consumption and environmental impact. Significant savings can be made by a suitable choice of materials and construction types. In this paper the ecological impacts of a new ultra-light and ultra-shallow flooring system and CoSFB/Cofradal system have been demonstrated for a typical 8.10m x 8.10m grid as illustrated in Tables 3 and 4.

It was found that the embodied energy and embodied carbon for the production stage of the new ultra-light and ultra-shallow flooring system are 90.19 GJ and 8.67 tonne CO_2 e. These are well comparable if not less than the figures for the production stage of the CoSFB with Cofradal system which are 106.25 GJ and 8.69 tonne CO_2 e, respectively. The values for the transport stage for the new ultra-light and ultra-shallow flooring system are 3.01 GJ and 0.19 tonne CO_2 e, also compares well if not less than the values of the CoSFB with Cofradal system with 5.24 GJ and 0.32 tonne CO_2 e, respectively. In addition, lower values have been observed from the end of life assessment of new ultra-light and ultra-shallow flooring system with 36.54 GJ and 2.12 tonne CO_2 e comparing with 46.63 GJ and 3.10 tonne CO_2 e for the CoSFB with Cofradal system, respectively. This indicates that the new ultra-light shallow flooring system is a valid solution and can provide an effective, a sustainable, and a valuable alternative solution to the construction industry in terms of both environmental performance and speed of construction while reducing site work and site risks.

REFERENCES

[1] Dong, Y.H., Jaillon, L., Chu, P. and Poon, C.S., (2015), "Comparing carbon emissions of precast and cast-in-situ construction methods–A case study of high-rise private building". *Journal of Construction and Building Materials*,Vol. 99, pp. 39-53.

[2] Stroetmann, R. and C. Podgorski, (2013), "Resource-efficient design of components for office buildings in steel composite construction". *Proceedings of the 7th International Conference on Composite Construction in Steel and Concrete,* New South Wales, Australia, 28-31July 2013, Vol. II, pp. 342-355.

[3] Meyer, C. (2009), "The greening of the concrete industry", *Journal of Cement and concrete composites,* Vol 31, No.8, pp. 601-605.

[4] Jaillon, L. and C.-S. Poon, (2008), "Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study", *Journal of Construction Management and Economics*, Vol. 26, No.9, pp. 953-966.

[5] Jaillon, L., C.-S. Poon, and Y. Chiang, (2009), "Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong". *Journal of Waste management,* Vol. 29, No.1, pp. 309-320.

[6] Bribián, I.Z., A.V. Capilla, and A.A. Usón, (2011), "Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential". *Journal of Building and Environment*, Vol. 46, No.5, pp. 1133-1140.

[7] Reddy, B.V. and K. Jagadish, (2003), "Embodied energy of common and alternative building materials and technologies". *Journal of Energy and buildings,* Vol. 35, No.2, pp. 129-137.

[8] Passer, A., Cresnik, G., Schulter, D. and Maydl, P., (2007), "Life cycle assessment of buildings comparing structural steelwork with other construction techniques". *Proceedings of the 3rd International Conference on Life Cycle Management.* Zurich, Switzerland, 27-29 August 2007. Vol. 3.

[9] Braun, M., Hechler, O., Hauf, G. and Kuhlmann, U., (2011), "Embodied energy optimization by innovative structural systems". *Proceedings of the 25th Final Conference of the Cost Action C*., Austria, 2-3February 2011.

[10] Tsavdaridis, K.D., C. D'Mello, and B.Y. Huo, (2013), "Experimental and computational study of the vertical shear behaviour of partially encased perforated steel beams". *Journal of Engineering Structures,* Vol.56, pp. 805-822.

[11] Maraveas, C., Tsavdaridis, K.D. and Nadjai, A., (2017), "Fire Resistance of Partially Unprotected Ultra Shallow Floor Beams (USFB): A Numerical Investigation". *Fire Technology*. 2017, pp. 609-627.

[12] Hechler, O., Braun, M., Obiala, R., Kuhlmann, U., Eggert, F. and Hauf, G., (2013). "CoSFB—Composite Slim-Floor Beam: Experimental Test Campaign and Evaluation". Proceedings of the 2013 International Conference on Composite Construction in Steel and Concrete, North Queensland, Australia, 28-31 July 2013, Vol. VII, pp. 158-172.

[13] Mateus, R. and L. Bragança, (2011), "Life-cycle assessment of residential buildings". *Proceedings of the 25th Final Conference of the Cost Action C*., Austria, 2-3February 2011, pp.255-262.

[14] Grant, A., R. Ries, and C. Kibert, (2014), "Life cycle assessment and service life prediction". *Journal of Industrial Ecology*, Vol.18, No. 2, pp.187-200.

[15] Hauke, B., Hechler, O., Axmann, G., Fischer, D., (2010), Environmental Product Declaration for structural steel as basis for sustainability assessment of constructions. COST Action C25 Final Conference *Sustainability of Constructions - Integrated Approach to Life-time Structural Engineering*, Innsbruck.

[16] Hammond, G., Jones, C., Lowrie, F. and Tse, P., (2008), *Inventory of carbon & energy: ICE*. Bath: Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath.

[17] Sjunnesson, J., (2005). "Life cycle assessment of concrete". Master thesis. Lund University; September 2005.

[18] Yang, K.-H., J.-K. Song, and K.-I. Song, (2013), "Assessment of CO_2 reduction of alkali-activated concrete". *Journal of Cleaner Production*, Vol. 39, pp. 265-272.