ABSTRACT
This paper presents the design of a multifunctional floor element. The floor element integrates multiple functions, such as structural and energy related aspects. This integration reduces material use, related space requirements and embodied emissions. The element is optimised for embodied energy in the structural domain, by using a vault and fin structural form. With this method, a significant volume of concrete is replaced by expanded polystyrene insulation at locations that improve the structural and thermal performance of the element. In the energy systems domain, improvements to operational energy are provided by an active hydronic heating/cooling system and a passive thermal mass resource. The thermal performance design was driven by the use of computational fluid dynamics with conjugate heat transfer effects. The main advantage is a reduction in thermal losses by minimising the connection between the radiant panel and the structural supports. This increases the heat flow density, resulting in a lower supply medium temperature and an improved system efficiency of the radiant panel. This work provides design guidance to the development of improved lifecycle energy buildings.

INTRODUCTION
As Europe moves towards 2050 greenhouse gas (GHG) emissions targets, an 80% reduction from 1990 levels, building regulation is encouraging design teams to follow innovative strategies to fully exploit the capacities of building elements (Grossmann et al., 2015). One approach towards this objective is the utilisation of innovative and multifunctional building elements. These elements integrate multiple functions, such as structural and energy related aspects, in a single element. This reduces material use, related space requirements and embodied emissions. In addition, it has the potential to improve energy efficiency and operational performance compared to traditional building systems.

This paper discusses the thermal design of a multifunctional lightweight integrated floor element, which will be implemented in an experimental residential research building (Figure 1). The reduction of materials is achieved by using a vault and fin structural form. With this method, a significant volume of concrete is replaced by expanded polystyrene insulation at locations that improve the structural performance of the element and the thermal efficiency of an embedded hydronic heating/cooling system. In this case, the multifunctional element has structural, architectural and energy system attributes.

The multifunctional element is focused on the utilisation of reinforced concrete. Due to its durability and adaptability, it is one of the most widely used structural materials in the construction industry. However, it also contains a high proportion of embodied energy due to the manufacturing process (Brunke and Blesl, 2014). Based on its physical properties, reinforced concrete has advantages when used as an active radiant building space conditioning panel. This is especially accurate when it is coupled with a low temperature renewable source, which require large radiant surface areas. These renewable onsite resources include ground source geothermal, solar thermal and thermal storage (Bauer et al., 2010). Further, passive thermal mass can also be utilised with a natural or mixed ventilation system (Balaras, 1996). Combining a structural element with an energy function reduces the requirements of providing heating/cooling equipment, which can result in a significant embodied energy saving. While multifunctional elements are complex and require a high level of technical expertise from a number of domains, it provides options for designers to develop improved lifecycle energy buildings.
The paper is organised in four sections. The first section provides background information to the research project, the structural aspects of the element and the building energy systems integration. The second section summarises the initial investigation using a literature review and numerical models with simplified geometry. In section three, a pipework routing strategy for the lightweight floor element is outlined and the pipework routing strategy is assessed by applying it to the full geometry. The conclusions are given in the final section.

BACKGROUND

This section provides background information relating to the overall NEST HiLo project, the structural aspects of the lightweight funicular floor and the building energy systems integration.

NEST HiLo project

NEST is a district scale building project by Empa (Swiss Federal Laboratories for Materials Science and Technology), to demonstrate innovation in the built environment (Empa, 2015). NEST (Next Evolution in Sustainable Building Technologies) provides a basic infrastructure and access to an advanced ground source geothermal system, in the form of the backbone, which can accept up to fifteen modular buildings (Figure 1). This creates a unique setting for academic groups and innovative companies to implement research under real-world conditions. NEST serves as an interactive demonstration and research facility for the design of sustainable buildings and districts. The construction of the NEST building was completed in Dübendorf, Switzerland, in late 2015.

As one of the first NEST modular buildings, HiLo will be a two bedroom apartment and will be used to host visiting academic and industry guests (HiLo, 2015). One of the key objectives of HiLo (High performance, Low energy) is to demonstrate that an integrated design process, which considers the lowering of both embodied and operational energy, allows for sustainable design solutions without severe architectural compromises. Further, HiLo will exhibit innovation in the domains of building energy systems and structural design (Figure 2). HiLo will be a net plus energy building in operation phase and will begin construction in early 2017.

Lightweight funicular floor system

The Lightweight funicular floor system has been developed by the Professorship of Architecture and Structure, Block Research Group (BRG), led by Prof. Dr. Philippe Block.
perimeter of the structure with tension ties. This structural system is optimised to achieve a concrete thickness of only 20 mm for both the vault and fins. The resulting structure is significantly lighter than traditional methods with a concrete (material) volume reduction of up to 70% (López López et al., 2014).

**Building energy systems integration**

Radiant panels perform well in terms of occupant comfort, system efficiency and installation cost (Lehmann et al., 2007). This is achieved through radiant and convective (total) heat transfer. A system is defined as radiant when the radiant heat transfer coefficient is greater than 50% of the total heat transfer coefficient (thtc) (ASHRAE, 2012). In comparison to air-based space conditioning systems, radiant systems offer a number of advantages. These include less equipment noise, less draft and an improved vertical air distribution (Catalina et al., 2009). Further, the utilisation of large surface areas results in a supply medium temperature of near room temperature for heating and cooling modes.

Ceiling radiant panels can be integrated in the structure of a building or can be added as a separate system. As it is thermally separated from the building structure, the separate system has an advantage of being more efficient. However, the extra equipment required increases the embodied energy of the building, increases the space requirements and can be visually intrusive. Thermally activated building systems are realised by integrating a hydronic pipe network within the structure of a building (Lydon et al., 2015). This converts an internal building surface into a radiant panel, which is used for heating or cooling purposes. One of the disadvantages of an integrated system is the strong connection to typically massive structural frames. This results in a longer time period to reach a steady state operating condition and an increase in thermal losses to the structural materials in the heating case.

The funicular floor addresses this problem by reducing the connection between the radiant panel and the structural supports. Further, the floor section is structurally optimised to significantly reduce the overall volume of concrete. This results in a significant saving in embodied energy and an improvement in the efficiency of the heating/cooling panel due to the thinness of the concrete section.

In addition, the internally exposed thin concrete surface can be utilised as a passive thermal mass resource. As the key layer for thermal mass relates to the first 20–30 mm, the thermal mass performance of the funicular floor should not be greatly reduced, in comparison to traditional sections.

It should be noted that the element is referred to as a floor. In terms of structures, this is accurate as the loading is applied to the floor surface. However, the important surface for energy systems is the ceiling surface.

**INITIAL INVESTIGATIONS**

This section discusses the key parameters used for the numerical models, a summary of the CFD setup and a study of the influence of the structural geometry on the radiant panel performance.

**Ceiling heat transfer coefficient**

Heat transfer coefficients are key parameters for the design of radiant panels, which are used for equipment sizing, system control and the thermal comfort assessment of a building interior. Existing experimental measurements have been used to select a suitable range of values for the CFD modelling. A review by (Rhee et al., 2015), noted that the radiant coefficient can be taken as 5.6 W/m² K and the associated convective component is dependent on the location of the panel (i.e. floor, ceiling or wall) and the mode of operation (i.e. heating or cooling).

A study by (Causone et al., 2009) investigated thtc’s at a ceiling surface in a test chamber of 4.3 m x 2.7 m with a ceiling height of 2.56 m. The results show a thtc for cooling of 13.2 W/m² K. This is slightly higher than other studies (11 W/m² K - Olesen, 2007). The variance could relate to a difference in reference temperature. The thtc for the heating mode was 5.8 W/m² K. This agrees with results of previous studies of 6 W/m² K (Awbi and Hatton, 1999).

In conclusion, our CFD models used a thtc of 6 W/m² K for the heating mode and 11 W/m² K for the cooling mode.

**Concrete thermal conductivity**

The three main reinforcing materials options for the concrete floor are steel mesh (or fibres), glass fibres and carbon fibres. As the use of steel reinforcement would change the thermal properties of the concrete panel, this section discusses the thermal conductivity of a steel mesh reinforced thin concrete panel. (Hawlader et al., 1990) conducted a thermal performance study on 200 mm test cubes using varying steel mesh spacing and orientations. The heat flow was measured through the samples, when a constant temperature was applied to a face of the cube and an array of thermocouples was used to estimate the heat flux at the opposite face. The results show that as the volume fraction of the reinforcement increases the thermal conductivity of the reinforced concrete sample increases and the time to reach a steady state condition decreases. The orientation of the steel mesh had a significant influence on the thermal conductivity test cubes. When the reinforcement mesh was orientated parallel to the direction of the heat source the range of thermal conductivity of the test cubes was (1.5 – 7.5 W/m K) and in a perpendicular direction (1.1 – 3.2 W/m K) depending on the reinforcement volume fraction.

A CFD simulation of a thin concrete panel with reinforcing mesh layers was used to estimate the design thermal conductivity value (Figure 4a). The model included four layers of 1 mm diameter, 12 mm
spacing steel mesh reinforcement (Figure 4b). Two layers were placed at the cover distance (2 mm) from upper surface and the lower surface. High strength concrete typically has a thermal conductivity of 1.65 W/m K (Hens, 2012). This value was used with the thermal conductivity of the steel reinforcement of 16.17 W/m K. A temperature contour plot of the reinforced and unreinforced sections, show an improvement in the heat distribution in the reinforced concrete section (Figure 4c-d). By comparing the surface heat flux of both results, the design thermal conductivity for the reinforced concrete panel was estimated at 1.85 W/m K.

**CFD setup**

ANSYS Workbench was used to generate a tetrahedral and hexahedral grid with prism layers at the wall of the fluid domain. The finite volume CFD code ANSYS Fluent 14.5, with the pressure-based solver, was used for all of the numerical simulations. The upwind spatial discretisation schemes were used for all of the parameters, except for pressure (ANSYS FLUENT, 2011).

Conjugate effects are used to model the heat transfer in the solid domain. For this type of analysis, it is important to ensure accurate representation of the fluid/solid and solid/solid connections. In some cases, this requires manual checking of the model geometry.

The turbulent component of the fluid flow was modelled using the Realisable k-epsilon turbulence model. Convergence was monitored and the simulation was continued until the residuals showed no significant change.

**Heat distribution of the floor element**

One of the main advantages of the funicular floor is the replacement of concrete with EPS insulation at locations that improve the structural and thermal performance of the element. For the thermal performance, this provides a level of control of the distribution of the heating energy transported by the hydronic system. To quantify the performance improvement, a simplified geometry (1.650 m x 1.500 m) of the funicular floor is compared to a traditional structural floor geometry. Figure 5a – 5c shows the simplified geometry of the funicular floor with insulation and structural fins. For the traditional floor geometry, the insulation is replaced with concrete. A heat transfer coefficient of 6 W/m² K was applied to all of the external surfaces. The heated medium of the hydronic system was liquid water with a supply temperature of 35°C and an inlet velocity of 0.5 m/s.

Figures 5d - 5g show the temperature contour plots of the top surface and a section of each geometry. As expected, the solid concrete floor has the highest heat losses at this surface (38% of the total heat transfer through all external surfaces). The funicular floor has an 11% heat loss through the top surface. The lower thermal losses of the funicular floor section translate to a lower supply medium temperature. For example, to match the ceiling surface heat density of the funicular floor, the thermal energy supplied to the traditional floor section had to be increased by 51%.
This indicates that, by improving the heat distribution, the funicular floor is a feasible method for a ceiling level radiant panel and that the structural fins have an acceptable impact on the thermal performance.

**HILO FLOOR CFD MODEL**

The main difference between the initial model and the full model is the complex geometry of the floor. This section discusses the design strategy based on the initial analysis and the geometry preparation.

**Design strategy based on the initial investigations**

The section thickness of traditional thermally active structural concrete ceiling elements is typically 150 mm. Therefore, the pipework spacing of traditional implementations of thermally active concrete elements are independent of the structural design. This results in a uniform loop layout, which can be a serial or a spiral pattern.

In the case of the funicular concrete floor, the pipework spacing is constrained by structural issues. These constraints are twofold. Firstly, if the intersections of the pipework with the structural fins are not close to perpendicular, the structural efficiency of the fin is reduced. Secondly, the structural fin absorbs thermal energy from the pipework, which reduces the efficiency of the hydronic system. Therefore, surface contact between the pipework and the structural fins should be minimised. This results in a loop layout strategy that respects the concrete structure with a non-uniform spiral pattern. The funicular floor system will be precast in a two-sided mould. The upper side of the mould will be milled EPS insulation blocks, which will act as permanent concrete formwork and a thermal insulation layer (Figure 6). This also provides a method to control the placement of the hydronic pipework during fabrication.

**Figure 6 Insulation block with pipework channels**

Additionally, the cut channel in the EPS insulation block allows the pipework to be encased in concrete. This provides a good surface contact between the concrete and the hydronic pipework, which improves the overall thermal performance. As the ceiling surface is curved, the thickness of the insulation varies from the floor centre point to the edges. Therefore, the spacing of the hydronic pipework is increased at the central section of the floor.
The addition of steel mesh layers or steel fibres to the concrete would improve the thermal transport properties of the floor element. For the Hilo project, the floor panels will be used to provide heating and cooling the bedrooms. As the heating demand of the bedroom is lower than the main space, the inclusion of steel reinforcement solely for thermal reasons may not be necessary.

**Geometry preparation**

The geometry for the floor is non-planer. This made it difficult to accurately place the pipework and the cover section in the model geometry. As grid generation is dependent on clean geometry, this was a key aspect of the analysis phase. The geometry could be simplified by removing the curved ceiling surface. However, this would result in a loss of analysis accuracy. In addition, the simplified model would be of little use for the fabrication preparation.

A Rhino/Grasshopper script (McNeel, 2015) was employed to overcome the complex geometry and fast track the thermal analysis. This was used as input to the connected structural and architectural designers. This reduces the process to a 2D planar method where loop routing strategies can be easily tested. Figure 7 shows the Rhino/Grasshopper script setup used to generate the pipework.

The Rhino command “project” creates curves or points on a surface that are the intersections of the surface and curves or points projected toward the construction plane (McNeel, 2015). When this project function was used, it projected a pipework centreline onto the ceiling surface with a high number of control points. This resulted in a computation geometry with a high number of small surfaces and generated a CFD mesh with errors and a high number of cell volumes. To resolve the problem the project and fillet command were modified to limit the number of control points and the fillet curve radius.

The Rhino/Grasshopper script takes an input of a polyline and outputs a pipework geometry. Planar geometry is extracted from the curved ceiling surface (Figure 8a). The pipework centreline is sketched in 2D (Figure 8b). This centreline is projected onto the curved ceiling surface. A number of parameters are set in grasshopper to generate the pipework tube and cover geometry (Figure 8c), which can be used to generate a suitable CFD mesh (Figure 8d).

**Results**

Based on the length of the pipework used per square metre of floor, the spacing is equivalent to a 175 mm spacing of a standard hydronic installation.

The heating case results show that the heat flow density at the ceiling surface is 47 W/m² with a supply temperature of 35 °C (Figure 9c). The cooling case with a supply temperature of 19 °C, results in a heat flow density of 41 W/m² (Figure 9d).

The results demonstrate that the integrated funicular floor has a suitable thermal performance for building applications.
Figure 8 Geometry preparation for the HiLo floor

(a) Planar geometry extracted from curved ceiling surface
(b) Pipework layout projected onto curved ceiling surface
(c) Generation of pipework and cover section geometry
(d) Final geometry for export to CFD software

Figure 9 CFD results for the HiLo floor element

(a) Temperature contour plot of the lower surface of the floor
(b) Temperature contour plot of a section of the floor
(c) Temperature contour plot of the lower surface of the floor (heating case)
(d) Temperature contour plot of a section of the floor (cooling case)
CONCLUSION

The funicular floor reduces thermal losses to the structure of a building by minimising the connection between the radiant panel and the structural supports. Further, the floor section is structurally optimised to significantly reduce the overall volume of concrete. This results in a significant saving in embodied energy and an improvement in the efficiency of the heating/cooling panel due to the thinness of the concrete section. In addition, the internally exposed thin concrete surface can be utilised as a passive thermal mass resource.

Based on the completed simulations, it is expected that the thin concrete radiant panel will reduce the time duration to reach steady state operating conditions, in comparison to a traditional concrete section. Further work will be completed to investigate the dynamic performance of the element. The research will be validated at the operational stage of HiLo using structural and thermal monitoring, which will be embedded in the building elements.

ACKNOWLEDGEMENT

The authors would like to acknowledge the contribution of Abel Groenewolt (Architecture and Building Systems), Diederik Veenaendaal and Tomas Mendez Echenagucia (BLOCK Research Group), Dave Pigram (Supermanoeuvre), Beat Lehmann (the Kanton of Zurich), the NEST team at Empa, the Swiss Federal Office of Energy and the various consultants involved in the project. This research was supported by Climate-KIC through the building accelerator (BTA) program.

REFERENCES


