Parametric numerical study on jointless macro synthetic fiber reinforced concrete industrial floors

Dr. Péter Károly Juhász[1], Péter Schaul[1,2]

[1] : JKP STATIC Ltd., Budapest, Hungary.

[2] : Budapest University of Technology and Economics, Department of Construction Materials and Technologies, Budapest, Hungary.

Abstract

The demand for jointless industrial floors is increasing, but there are no relevant agreed-upon standards or design recommendations, particularly for floors made of synthetic fiber reinforced concrete. The primary challenge associated with jointless floors is controlling the cracking caused by the restrained movement of concrete due to shrinkage and temperature changes. In addition to predicting the stress and cracking that will arise from service loads, investigation of long-term effects requires significant attention. This study conducted a parametric numerical analysis of industrial floors, with typical joint spacings ranging from 6 to 25 m and a thickness of 200 mm evaluate long-term shrinkage and temperature effects under typical load conditions (Uniformly Distributed Load, UDL). Numerical studies were conducted using the ATENA finite element software, with the effects of fibers was modeled using the modified fracture energy method. The main goals of this study were to develop a practical design methodology and define the maximum acceptable crack-width during the lifetime of the floor. Additionally, the relationships among the geometrical dimensions, material properties, and loads of an industrial floor were depicted as a diagram, which can serve as a reference for designing joint distances.

Keywords

FRC, jointless, industrial floor, numerical analysis, finite element

1 Introduction

In case of industrial buildings, the design of industrial floors has traditionally played a secondary role, as designers prefer to delegate this task to contractors, mainly due to the lack of a usable technical guideline. Contractors can draw on their decades of experience to design floors based on their intuitions, using various technologies and materials.

There are some contractors who prefer to use reinforced concrete industrial floors. However, considering the increasing cost of labor and steel materials, macro synthetic fiber reinforced concrete (FRC) floors are becoming increasingly popular. In fact, one of the primary uses of synthetic fiber reinforced concrete today is in industrial floors. However, there is a general consensus among contractors and designers that a good design is essential for constructing a floor with adequate load-bearing capacity.

Previously, floor dilatations were typically designed at intervals of 5 to 6 m by saw-cut joints. However, *jointless floors* have gained considerable popularity. This term does not refer to the complete elimination of dilatations but rather to a significant increase in dilatation spacing, typically on the order of 20 to 30 m. The main advantage of this type of floor is that vehicles (typically forklift trucks) operating on such floors have longer service lifetime because the wheels are subject to the maximum wear when passing over dilatations. Additionally, large-plank floors are preferable from the perspective of construction (with no requirement for subsequent notching) and aesthetic (notches are less intrusive in stores with no need for concrete paving).

Despite its numerous advantages, there are several difficulties associated with jointless floor design. Chief among these difficulties are the stresses in such floors caused by shrinkage and temperature changes, which increase with the floor size, resulting in cracks in the floor exceeding acceptable limits if the floors are improperly designed/reinforced/concrete-engineered. The design of such floors requires particular care because the effects mentioned above may result in substantial initial stresses, with the effects having to be considered when valuating loads. For live loads, their value, types, locations and variations over time should considered.

This study aimed to develop a design methodology that determines the maximum allowable initial stress that can be generated on a floor for a given floor geometry and load.

2 Construction of industrial floors

Industrial floors are complex structures, and their load-bearing capacity depends on their geometry, materials used, relationship with the main structure, underlying bedding and the relationship between the floor and bedding. In all cases, the complete construction of a concrete floor comprises at least three structural elements: the compacted load-bearing subbase and subgrade, separating layer and floor itself.

2.1 Soil and bedding

In most cases, a form of crushed stone bedding is applied underneath industrial floors. However, the subsoil parameters underneath the bedding are important, because they play a role in the floor settlement. The compactness of the subsoil is typically determined by the bedding factor k, compressive modulus E_{v2} or *CBR* (California Bearing Ratio). It is necessary to verify at least one of these values for all floor construction projects. A compression test in accordance with DIN 18134 can be used to verify this, in which the subsidence of the loaded plate is measured and the modulus of elasticity is calculated from the subsidence value. The value obtained after the first loading is E_{V1} and the value obtained after the second loading is E_{V2}.

2.2 Interface layer

Regarding stresses caused by shrinkage and temperature changes, it is critical to determine the relationship between the floor and bedding. This is because the magnitude of forced loads on the floor is also influenced by the manner in which the floor is embedded into the substructure. The main design goal is to reduce the coefficient of friction μ as much as possible, which can be accomplished by installing two layers of foil and levelling the upper plane of the bedding. In this case, the coefficient of friction associated with the first cracking event is approximately 0.75 and the recommended coefficient for repeated displacements is approximately 0.3 (Lohmeyer 2011).

2.3 Characteristics of FRC floors

For FRC materials, the main material parameters are the compressive strength, elastic modulus and uniaxial tensile strength of concrete, all of which stem from the definition of concrete strength classes. Additionally, the residual flexural tensile strength values for a given fiber type and dosage must be determined. Beam tests are some of the most widely used methods for evaluating flexural-tensile strength and residual stress after cracking. The European standards define the three-point notched beam test in the EN 14651:2005+A1:2007 standard. TR34 (The Concrete Society, 2016) calculates design values of residual flexural strength directly from the mean values, whereas the *fib* Model Code 2010 (2012), used in numerical analysis, calculates design values from the characteristic values, which are the 5% lower quantile of the results.

3 Effects and loads

Over its lifetime, an industrial floor is subjected to various loads in different phases. Immediately after casting, the stresses caused by shrinkage will be particularly relevant, whereas during the use of a floor live loads (such as shelf legs and vehicle traffic) and even coincident thermal effects will become more relevant.

3.1 Shrinkage and thermal effects

Concrete undergoes deformation during shrinkage. However, the friction between a floor and a bedding prevents free movement, leading to the generation of tensile stresses in the floor. The amount of stress depends primarily on the geometry of the floor, magnitude of friction, which is determined primarily by the interface layer, and the value of shrinkage. Similar effect can be observed as a result of temperature differences (Lohmeyer 2011) and such effects also vary with the thickness of the floor (Heath, Roesler 1999).

Notably, the temperature effects can occur within a daily timeframe, whereas the shrinkage process is much slower and can take years. Stresses caused by long-term shrinkage can also relax as concrete creeps, which is a complex process.

3.2 Loads

Industrial floors are typically classified into the following three groups based on the type of load: point (such as loads of shelf legs, and vehicle wheels), linear (such as loads imposed by walls or rails), and surface (such as materials stored on a surface, where large supports are treated as surface loads).

These effects cause stress to build inside a floor. When designing a floor, it is of utmost importance that the stresses caused by external forces are considered in combination with those internal effects because the actual load bearing capacity of a structure may be lower than the designed value if only specified external loads are considered.

4 Special design considerations for jointless industrial floors

The structural design of industrial floors can be performed on analytical methods for surface supported slab structures (TR34 and ACI). By using these analytical equations, the maximum loadbearing capacity can be determined for different types of loads acting on a floor surface. In most cases, calculations are only performed for force loads that may be located at internal position, on a dilatation or free edge, or in a free corner. Standards and guidelines require the upper surface to be free of cracks for point loads but allow cracking the lower surface. This design method uses the formulas presented by Meyerhof (1962), based on the yield line theory. This method can handle cracked reinforced concrete, traditional steel bar reinforced concrete, or fiber reinforcement. For line and surface loads, the elastic formulas presented by Hetényi (1971) are used to model the cross-section of un-cracked concrete.

However, these guidelines typically do not address the initial stresses caused by shrinkage or temperature effects and if they do, they simply subtract the values of these stresses from the tensile strength of the concrete in the form of a simple restraint stress. Handling these stresses in such a manner approximates the detriment to safety in cases where the floor is either subjected to significant thermal effects (such as cold storage rooms, outdoor structures) or where the stresses caused by shrinkage are non-negligible (e.g., jointless floors). Such stresses reduce the overall load bearing capacity of a floor, which in turn reduces the force load that can be applied to the floor.

The key issue in the design of jointless industrial floors is to consider shrinkage and thermal effects when calculating load bearing capacity of a floor, and to model the floor in a cracked state considering the crack width.

There are two main trends for creating the separation layer between a floor and subbase when designing jointless floors. The first is to link the floor to the subbase and provide the highest possible friction coefficient so that the floor can move with the bedding, or be supported by the bedding in the horizontal direction. The prevention of movement generates stresses that cause cracks in concrete, but these cracks cannot be localized based on the strain hardening material parameters induced by high amounts of reinforcement (such as steel bars or steel fibers). Conversely, a layer with the lowest possible coefficient of friction can be installed between a floor and bedding to allow the floor to move freely in the horizontal direction. In such cases the stress generated during movement will not reach the tensile strength of the concrete, but if it does, the added fiber reinforcement will limit the opening of crack. In this study, the behavior of macro synthetic fibre reinforced concrete industrial floors were investigated, adopting the latter design methodology.

Our goal was to model the initial stresses on a floor as a function of floor geometry and material parameters. In some cases, different permanent loads cause different movements/stresses leading to floor cracking. These relationships can be used to determine the maximum allowable shrinkage or expected crack width. The determined initial stresses can also be considered in analytical calculations, and additional loads can be included in numerical model.

5 Research matrix

For jointless industrial floors, the stresses generated during shrinkage are highly dependent on the friction between the floor and subbase (Figure 1c). Under higher loads, more friction is generated, which causes higher stresses. The amount of stress depends not only on the magnitude of a load but also on its location on the floor surface. First, a general surface load was defined under which the generated stresses were maximized. Accordingly, two types of loads are considered: two (2SL) and four-sided (4SL) edge strip loads (Figure 1a and 1b).

Our first test was designed to derive the general load geometry. In this initial test 5%, 10%, 15%, 20%, and 25% of the edge length was loaded to determine the critical loading configuration. The results indicated that the crack widths were maximized when 10% of the edge was loaded, so this value was used for further analyses.

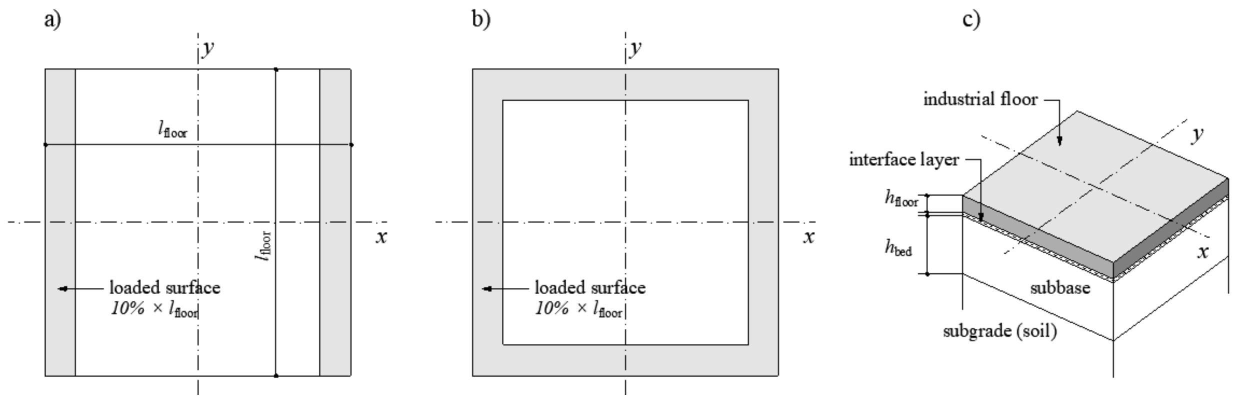

Figure 1: Two-sided load (2SL) (a); four-sided load (4SL) (b); construction of industrial floor (c)

Based on the obtained load geometry, industrial floors with different slab were investigated, where the variable parameter was the floor side dimension, l_{floor} (Figure 1a). The constant and variable floor parameters are listed in Table 1. In all cases, the shrinkage load was modeled under a temperature load with a value of –40 °C. This value corresponds to a strain effect 480 × 10^{-6}. This analysis was conducted to determine the maximum permissible elongation for each criterion. The hardening phase of the concrete was not taken considered in these tests, and the assumption of crack-free concrete can be considered an acceptable approximation with appropriate curing. Additionally, the long-term creep of industrial floors was not considered, which results in the relaxation of shrinkage stresses, meaning our tests were conservative approximation in favor of safety.

The goal of this study was to determine the stresses, crack patterns and crack-widths at different shrinkage values. For each floor, the allowable stress values were investigated for three criteria: the stress associated with the first crack, stress associated with the first crack on the upper surface of the floor and stress associated with a crack-width of 0.3 mm.

Table 1: Research matrix

Parameter name	Parameter type	Symbol	Value
Thickness of the floor	constant	h_{floor}	200 mm
Thickness of the bedding	constant	h_{bed}	300 mm
Concrete strength class	constant	*con*	C25/30
Fiber dosage	constant	*dos*	4 kg/m^3
Joint distance	variable	l_{floor}	6 / 8 / 10 / 12 / 15 / 20 / 25 m
Load value	constant	q_{UDL}	50 kN/m^2
Load type	variable	-	two-sided / four-sided

6 Numerical models

Numerical studies were conducted using ATENA finite element software (Cervenka Consulting, 2023). The failure criteria used for the concrete material model were the William-Menétrey criterion (1995) for compression and the Rankine criterion (Cervenka, 2008) for tension. The fibre reinforced concrete material parameters were defined according to the *fib* Model Code 2010 (2012), and the effects of fiber reinforcement were modeled using the modified fracture energy method (Figure 2) (Juhasz, 2018). The creep effects of synthetic fibers have been investigated in the past (Babafemi et al. 2018) and in our analysis they were modelled as a reduction in the residual strength values by a factor α=0.5 according to the results of previous studies. This factor should be investigated further in further studies. The used modified fracture energy value in this study corresponds to 4 kg/m^3 BarChip 48 synthetic macrofibre reinforcement. For the crack opening, the software uses the crack band theory proposed by Bazant (1983).

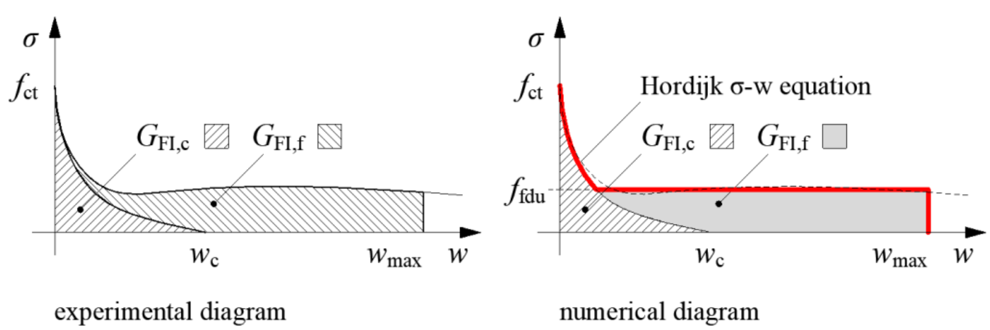

Figure 2: Used material model for fibre reinforced concrete

The floor and the subbase were modeled with 3D finite elements using double symmetry to reduce the number of elements. Between the floor and bedding, the displacement of the floor was modeled using contact elements. where the friction coefficients could be defined. The bedding was supported by nonlinear springs representing the stiffness of the subsoil. Such springs can only act under compression. The primary material parameters are listed in Table 2.

Standard isoparametric linear brick eight-node elements were used with full integration with a Gaussian quadrature with eight integration points. Appropriate energy dissipation, independent of finite element size, was modeled using the crack band approach, where the crack band size was calculated as a projection of the finite element size in the direction normal to a crack. This approach typically uses a different crack band size for each integration point on a finite element, because the band size depends on the concrete volume corresponding to the integration point and crack orientation.

The element sizes for the concrete slabs were 5 × 10 × 10 cm, meeting with the requirements that minimum four elements should be through the height of each section, and the aspect ratios were less than the recommended maximum ratio of 1:4 based on the findings of previous validation studies. For the soil volume, only two elements were used through the height (Figure 3).

All models were subjected to two parameter intervals. First, the own weight of the slab and a UDL were added in 20 steps. Second, the temperature effect was added in 300 steps. The temperature effect was added in the form of a linear distribution with a variation of 60% along the section, as recommended in the literature (Heath, Roesler 1999). The value at the top of the section was −40 °C whereas at the bottom it was −24°C (Figure 3). These values correspond to strain effect values of 480×10^{-6} and 288×10^{-6}. All parameter interval steps were stored during the analysis. The corresponding equations were solved using the Pardiso solver with the iteration limit set to 200. For non-converged steps the iteration with the lowest error between 100 and 200 iterations was selected.

Table 2: Material parameters

Material parameter name	**Symbol**	**Value**
FRC, compressive strength	f_c	25 MPa
FRC, tensile strength	f_t	1.8 MPa
FRC, fracture energy	$G_{FI,c}$	45 N/m
FRC, elastic modulus	E_c	31 GPa
FRC, added fracture energy	$G_{FI,f}$	1700 N/m
FRC, critical crack width	w_{max}	3.5 mm
FRC, creep factor	α	0.6
Contact, friction	μ	0.3
Subbase, elastic modulus	E_s	130 MPa
Soil, spring modulus	E_k	130 MPa

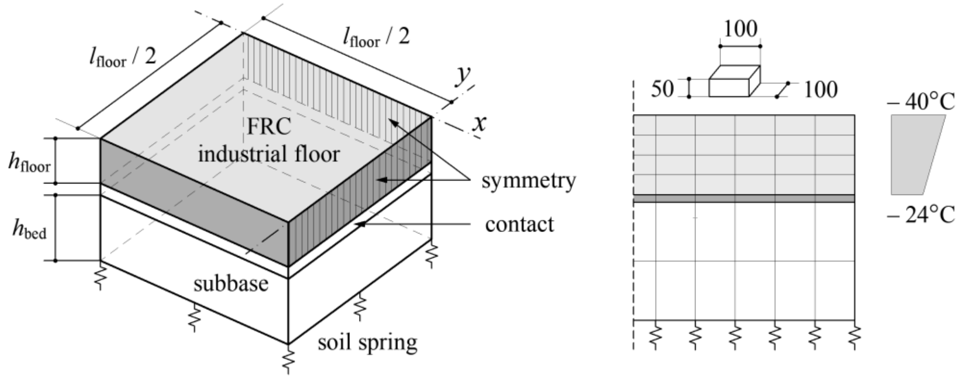

Figure 3: Numerical model (left); mesh and temperature distribution of the numerical model (right)

7 Results

Based on the results of the finite element analysis, the critical strain effect values and maximum crack widths as functions of the dilatation length are presented in Figure 4. Based on these diagrams, the strain limits of the aforementioned criteria were defined for different joint distances. Notably, the defined strain limits include both shrinkage and thermal effects.

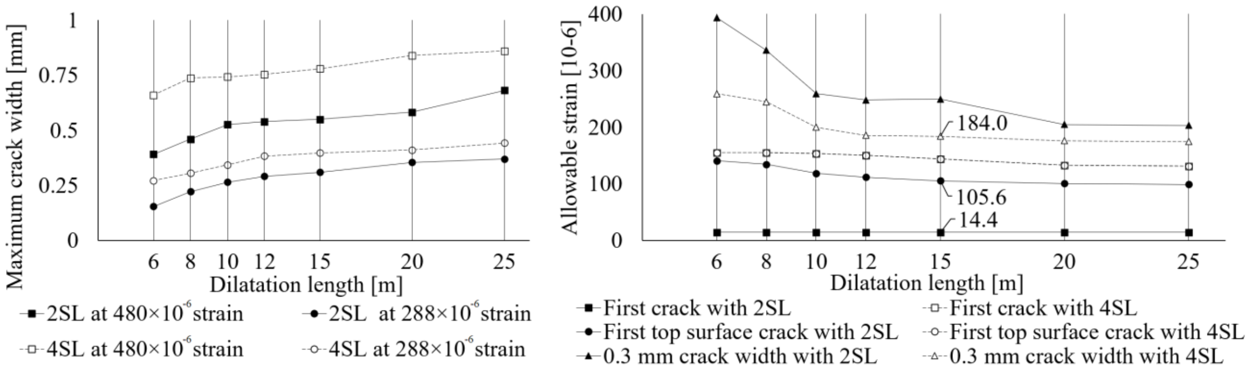

Figure 4: Maximum crack widths (right); allowable strains (left) in the function of dilatation length

It is apparent that the first crack appears at a very low strain level, meaning that a crack free structure is difficult to achieve when considering two-sided loading condition. At four-side loading it is significantly different, the first top surface cracks appear at the same strain level as the first cracks. On floors where loads are only imposed temporarily (for example car or truck parking areas, pathways), friction has less effect on the floor, leading to a better performance, making a crack-free floor possible with greater joint spacing.

With 0.3 mm crack-width criteria it is possible to extend the dilatation length up to 25 m. However, in this scenario the strain effect of the floor must be limited to approximately 180×10^{-6}. This can be achieved by using shrinkage reducers and controlling the effect of temperature. Figure 4 shows, that the strain level for 0.3 mm crack-width has not changed after 15 m dilatation length significantly. This phenomenon can occur, because above a certain strain level more and more cracks will appear and the floor start to behave like individual elements between the cracks. This phenomenon can be seen also in Figure 5.

In the case of four-sided loading, the results were more unfavorable considering the 0.3 mm crack-width criteria. In Figure 5, one can clearly see that the cracks are wider, and the crack propagation differs compared to two-sided loading. For two-sided loading, the main cracks were almost parallel to the loaded edge. For four-sided loading, the corner area was disturbed and the parallel cracks were connected. Notably, while the first crack formed slowly for two-sided loading, for four-sided loading, the first cracks appeared very quickly and the initial crack-width was large (more than 0.15 mm).

A particular example of how to use the diagram presented above for design purposes is provided below. If the joint size of the floor is set at 15 m, then the first step is to define the design criteria for the floor. If one criterion is crack free structure, then the allowable strain effect should be limited to 14.4×10^{-6}, which is an intractably low value. However, if cracks can appear on the bottom surface and only the top surface must be crack-free, then this value changes to 105×10^{-6}. If a 0.3 mm crack-width is allowable in the structure, then a 184×10^{-6} strain limit should be defined. Once the allowable strain level is determined, the structure is verified for live loads. If the concrete remains un-cracked, then it is possible to verify the maximum stress using the finite element model and add it as a restraint stress for analytical calculations. Traditional industrial floor design can be performed according to the codes. If the concrete cracks, then live loads can be calculated using the finite element model. In this case loads act on a floor that has already cracked and moved, and the corresponding capacity can be calculated.

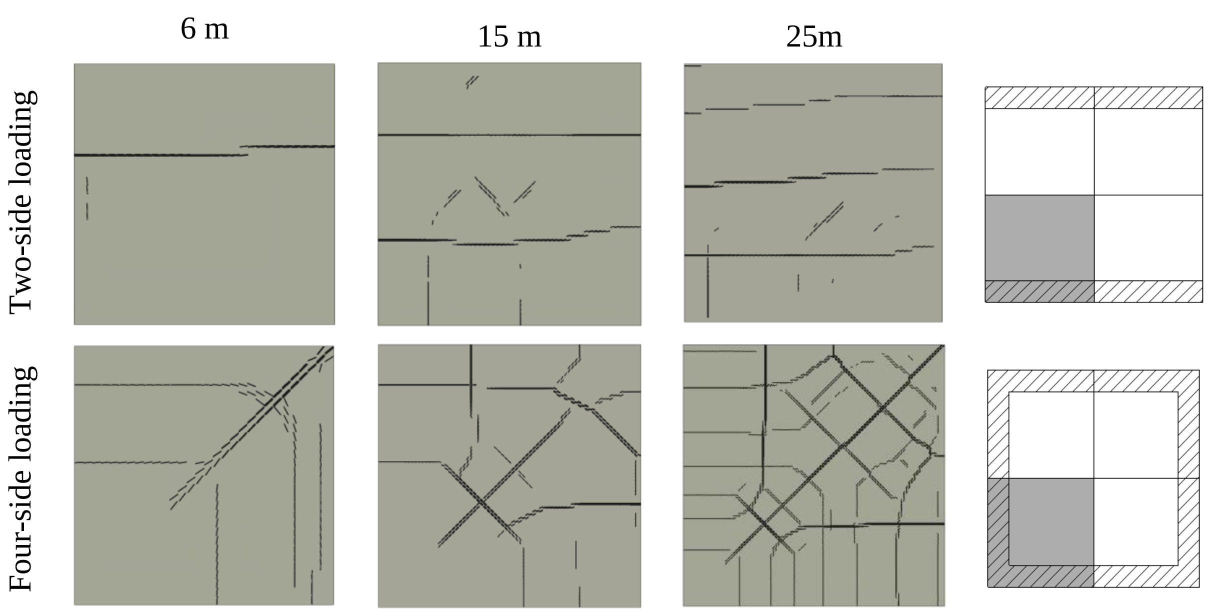

Figure 5: Crack propagation of 2SL and 4SL at 6 m, 15 m, and 25 m, with symmetry condition

In future research, the effects of concrete hardening should be investigated. During the first few hours, when concrete has very low strength, cracks can easily appear due to shrinkage, which can modify the final crack propagation and stress distribution. To this end a time-dependent material model can be adopted, where the hardening of concrete can be followed by adding the functions of the material parameters of concrete over time. Previously, a concrete floor with synthetic fibre reinforcement and its crack propagation has been modeled using this method (Juhász et al. 2015). Additionally, an analytical model can be developed based on the results of finite element analysis for cracked concrete. By modifying the formulas of modeling codes, the effects of joint size can be incorporated into analytical solutions.

8 Concluding remarks

There is a growing demand for jointless industrial floors, but there are corresponding no agreed upon standards or design recommendations, particularly for floors made of synthetic fiber reinforced concrete. The main advantage of this type of floor is that vehicles (typically forklift trucks) running on such floors have longer service lifetimes, because the wheels are subjected to the most wear when passing over dilatations. Additionally, large-plank floors are preferable from both a construction perspective (no need for subsequent notching) and aesthetic perspective (notches are not intrusive in stores and do not require concrete paving).

Despite its numerous advantages, there are various difficulties associated with jointless floor design. The most important of these are the stresses in floors caused by shrinkage and temperature changes, which increase with the floor size and can cause cracks to exceed acceptable limits if the floors are improperly designed/reinforced/concrete-engineered. Furthermore, maintenance in response to such crack occurrences is time-consuming and expensive.

The key issue in the design of jointless industrial floors is to consider shrinkage and thermal effects when calculating the load-bearing capacity of a floor and to model a floor in cracked state, considering of the crack-width.

The results and design methodologies presented in this paper can be useful for engineers who plan to analyze the effects of dilatation length on FRC industrial floors. The maximum allowable strain level can be defined and used for further live-load calculations and concrete mix designs. In future research, modeling results should be obtained by examining the effects of different thicknesses, concrete strength classes, friction parameters, and loading conditions.

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