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Design of Industrial Floors—TR34 and Finite Element Analysis (Part 2)

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Abstract: The design of industrial floors will be presented in this paper. In the first part of this article the calculation methods of the TR34 British guideline will be discussed. In the second part the state of the art design methods using advanced finite element methods will be presented. The design itself may seem as slow considering the actual computer efficiency, however comparing the results to theoretical analysis and to designing methods, precision and economical nature of the method can be justified. A large number of foreign industrial floor designs were made by this method; some of them will be shown as reference at the end of the article.

Key words: Industrial floors, TR34, FEA (finite element analysis).

1. Introduction

From a structural viewpoint industrial floors are slab structures supported on the lower surface. Essentially this static problem can be modelled in the easiest way by supposing linear springs (Winkler-type foundation), while the slab can be modelled by applying linear material model. This modelling method is more or less adequate until the cracking of the concrete, as from that point the structure will behave variously according to the type of the reinforcement. As the appearance of micro-cracks is nearly inevitable during the construction of concrete industrial floors, even this simplest form of modelling can be applied without exceptions. Nevertheless, most of the designing guidelines are based on this supposition, such as the British TR34 guideline [1].

In the first part of this article the opportunities of the industrial floor design provided on a daily basis are introduced, including the formulas and designing formulas used by the TR34 guideline. As these formulas consider significant approximations, they can only be used to certain load patterns, and they define load capacity of the floor with great safety, therefore in some cases there might be a need for preparing a design that is otherwise not possible based on the above mentioned guideline. Such design can be for instance a complex load situation, the variable cross section of the floor or the inequality of the subgrade. In these cases, it is possible to carry out FEA (finite element analysis), by which load capacity of the floor can be defined even with the previously mentioned conditions as well. FEA is a tool in the hands of engineers, which, next to the proper non-linear material models, geometrical models and support conditions, indicate the real behaviour of the structure at a given load. Although it is important to note that the behaviour of concrete structures is rather difficult due to the complex fracture mechanism, accuracy can only be achieved by special software. However, there is a chance to predict real crack propagation and displacement, and to optimise the

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structure, therefore in certain cases its application is inevitable.

2. Structural System of Industrial Floor

The industrial floor is a structure supported linearly on its bottom surface and is completely independent of the main structure of the building. Its goal is to transfer the loads to the subbase, then to the soil. In case of bad soil condition the industrial floor could be furthermore supported by piles, but in this case the design method is more difficult and the floor could only be made with traditional steel bar reinforcement.

The typical layers are the followings:

- subgrade;
- sub-base;
- (insulation);
- slip membrane;
- concrete industrial floor.

2.1 Sub-base

The examination, preparation and compaction of the soil under the industrial floor are essential, because this soil is the only support of the structure. The compaction is taken into account in the calculation with the subgrade modulus (k), whose unit is N/mm^3. To specify this, the DIN 18134 [2] standard can be used.

The subbase under the industrial floor could be many types; the choice depends mostly on the soil parameters. If the subbase parameter is unknown during calculation, then the minimal requirement could be determined which must be verified before the construction. The recommended minimum value is $k = 0.03\ N/mm^3$.

2.2 Concrete Industrial Floor

Formation and reinforcement of the industrial floor could be multifarious. In the case of small loads, the industrial floor could be made of plain concrete, in the case of bigger loads it could be made of fibre reinforced concrete and finally, in the case of extremely big loads it could be made of hybrid solution (steel bars and fibre reinforcement). The appropriate parameters of the concrete mix (cement and sand content, grading curve, water cement ratio, etc.) are very important, just as the joints and dilatations which could reduce and control the crack propagations.

2.2.1 Material Model of Concrete

During design it is very important to determine the parameters of the concrete which mainly depend on the concrete strength class. These parameters define the strength and strain characteristics of the concrete, which is the main input during the design. Parameters defined in the Eurocode 1992-1 [3] could be used for the design.

2.2.2 Formation of the Joints

In the industrial floor there is a need for forming a joint at specified distances to prevent the creation of high tensile stress, which could lead to the cracking of the floor. With the help of these joints the cracks could be localised and the surface of the floor can be crack-free. There are several types of joints for different requirements, as follows:

Sawn movement joint (free or restrained): designed joints to localise the crack. A saw-cut will be made when the concrete is strong enough to be cut without damaging the upper 1/3 part of the section. The ratio of slab dimensions between the joints must be between 1 and 1.5.

Formed movement joint (free or restrained): the first part of the slab will be poured between formworks. After the concrete is hardened this will be used as a formwork and the next slab will be poured to it. Because of this the extension of the concrete is limited.

Isolation joint: these types of joints are made at the edges of the slab to prevent any restraint to the slab by other structures.

The joint can be formed by using dowels or prefabricated steel elements. Joints are designed to provide a minimum of restraint to horizontal movements caused by drying shrinkage or temperature changes, while restricting vertical movement.

There are many types of prefabricated joints on the market, from the relatively simple to the engineered and optimised ones. One of the latest prefabricated steel joints is the Belgian HCJ (Hengelhoef Concrete Joint) which not only produces a strong connection between the slabs but because of its special waved design it makes the crossover of the wheels smooth. Thanks to its shape it gives a longitudinal and also transversal stiffness to the edge of the slab, providing a still researched special advantage to the slab.

3. Loads on Industrial Floor

Loads of industrial floors can be diverse due to the different functions. Based on the size of the loaded surface point load, line load and uniformly distributed load can be defined. During the design of slabs, the maximum live load threshold on the surface of the slab is required to be defined, and when that value is increased by the value of the safety factor, the structure is required to be designed in the ultimate limit state, as well as the characteristic value in serviceability limit state. According to this load bearing capacity of the slabs is kN/m^2. In the case of industrial floors this value does not tell much about threshold loads when using industrial floors, moreover, threshold surface load of the lower surface due to the industrial floor supported on the lower surface barely causes moment in the floor (the floor can subside, vertical normal stress is generated, which is a magnitude lower than the compression strength of the concrete). Moment is generated in the floor when these loads affect the floor periodically. There is a load state when the negative moment and the positive moment both take maximum value. Exaggerating load values is a common problem during defining uniformly distributed loads. The load of 100 kN/m^2 can not really occur in reality, it is rather hard to imagine that such a load is stored on the surface of the floor laid down, as typically these are stored in shelves or in containers. These containers have legs, which transfer point load to the industrial floor. During design it is worth considering the materials expected to be located on the floor or expected to be stored (in shelves, containers), the machines operating on the floor and vehicles using the floor (forklifts, trucks) as a starting point at defining loads, rather than using values provided as surface loads. In case the function of the floor is unknown, only the maximum values can be defined, which later require adjustment.

4. Analytical Design

The main calculation methods of the British TR34 guideline are demonstrated in this chapter. The guideline considers the concrete floor laying on the soil as a slab of flexural sub-base and thus refocuses the calculation on fracture mechanics foundations, by which the nonlinear state after the appearance of cracks can also be calculated. The soil behaving as a flexural material is modelled by Winkler-type springs.

4.1 Determination of the Flexural Tensile Strength of the Concrete

Flexural-tensile strength of concrete is not a material parameter; it rather depends on the thickness of the structure (h), so it considers size effect. These values are required to be determined as the basis of the calculation using the applied geometry and material properties with the help of the function below:

$$f_{\text{ctd,fl}} = f_{\text{ctm}}\left(1.6 - \frac{h}{1000}\right)\gamma_{\text{m}} \qquad (1)$$

where:

f_{ctm}: mean value of tensile strength of concrete;

h: thickness of the slab.

4.2 Moment Load Bearing Capacity of the Cross-Section of the Slab

In the following there is an opportunity to define the moment load bearing capacity of the industrial floor. In this case the floor needs to be categorized into various types according to the reinforcements applied, which are the followings:

- plain concrete;
- reinforced concrete;
- steel- or macro-synthetic fibre reinforced concrete;
- hybrid reinforcement concrete (applying fibre reinforcement and traditional reinforced concrete together).

According to the TR34: "Micro-synthetic fibres do not provide any post-crack ductility. They do not control cracking of the hardened concrete and therefore can not be used in lieu of other reinforcement. They are not considered in the design process."

In the case of plain concrete (also the fibrillated):

$$M_{\mathrm{un}} = f_{\mathrm{ctd,fl}}\left(\frac{h^2}{6}\right) \tag{2}$$

In the case of reinforced concrete:

$$M_{\mathrm{u,RC}} = \frac{0.95 A_{\mathrm{s}} f_{\mathrm{yk}} d}{\gamma_{\mathrm{m}}} \tag{3}$$

where:

A_{s}: area of steel reinforcement;

f_{yk}: characteristic value of yield strength of steel reinforcement;

d: effective depth of the slab;

γ_{m}: material safety factor for concrete.

In the case of fibre reinforced concrete (FRC):

$$M_{\mathrm{u,FRC}} = \frac{h^2}{\gamma_{\mathrm{m}}}\left(0.29\sigma_{r4} + 0.16\sigma_{r1}\right) \tag{4}$$

For the calculation of residual flexural tension strength it is necessary to define average tensile strength, to which RILEM TC162 [4] provides recommendations at two different values of CMOD (crack mouth opening displacement) (0.5 and 3.5):

$$\begin{aligned} \sigma_{r1} &= 0.45 f_{R1} \\ \sigma_{r4} &= 0.37 f_{R4} \end{aligned} \tag{5}$$

There are also formulas for hybrid solutions for different steel ratios.

4.3 Design for Point Loads

Based on the location of the load there are different design methods:

- internal condition: in this case the load is at least at a distance of $l + a$ from each edge or joint of the floor;
- edge condition: in this case, the load is at a distance lower than $l + a$ from one of the edges of the floor, and higher than $l + a$ from the other edges of the floor;
- corner condition: the load is at a distance lower than $l + a$ from both edges of the floor;

where:

a: the radius of equivalent contact area of the load, i.e. the radius of the circle which has the same area as the actual loading plate;

l: radius of relative stiffness, see Eq. (6).

$$l = \left[\frac{E_{\mathrm{cm}} h^3 10^6}{12\left(1-\nu^2\right)k}\right]^{0.25} \tag{6}$$

Functions and their mechanical backgrounds below can be found in Ref. [5]. Each correlation has two types depending on the a/l ratio.

Internal condition:

$$a/l = 0 \qquad P_{u,0} = 2\pi\left(M_{\mathrm{p}} + M_{\mathrm{n}}\right) \tag{7}$$

$$a/l > 0.2 \quad P_{u,0.2} = \frac{4\pi\left(M_{\mathrm{p}} + M_{\mathrm{n}}\right)}{1-\left(\frac{a}{3l}\right)} \tag{8}$$

Edge condition:

$$a/l = 0 \qquad P_{u,0} = \frac{\pi\left(M_{\mathrm{p}} + M_{\mathrm{n}}\right)}{2} + 2M_{\mathrm{n}} \tag{9}$$

$$a/l > 0.2 \quad P_{u,0.2} = \frac{\pi\left(M_{\mathrm{p}} + M_{\mathrm{n}}\right) + 4M_{\mathrm{n}}}{1 - \left(\frac{2a}{3l}\right)} \tag{10}$$

Corner condition:

$$a/l = 0 \qquad P_{u,0} = 2M_{\mathrm{n}} \tag{11}$$

$$a/l > 0.2 \quad P_{u,0.2} = \frac{4M_{\mathrm{n}}}{1 - \left(\frac{a}{l}\right)} \tag{12}$$

where:

M_{n}: negative moment capacity according to Eq. (2);

M_{p}: positive moment capacity according to Eq. (3) or Eq. (4).

Kaliszky derived the load bearing capacity of a reinforced concrete slab on a linear elastic foundation loaded by a point load in Ref. [6] based on the equality of the fracture moment and the work of external load, resulting in a formula identical to the result of Meyerhof, Eq. (7):

$$P_t = 2\pi\left(1 + \mu\right)m \tag{13}$$

where μ is the ratio of the positive and negative moment capacity.

The deduction ignores the punching shear failure and deals with an infinite plate. An interesting result will be given from the formula that the maximum load is independent from the load bearing capacity of the subbase. If the size of the loading plate is taken into account according to the formulas of Meyerhof, the maximum load also depends on the subbase modulus, but only slightly. The TR34 also deals with the situation of two and four point loads. For the shear design of the industrial floor the guideline recommends the punching shear design formulas of the Eurocode [3].

4.4 Design for Uniformly Distributed Load

The design for the distributed load is according to the formulas deducted by Hetenyi [7]. The negative (hogging) and positive (sagging) moments caused by the distributed load can be specified with the help of the parameter of λ, which can be calculated according to Eq. (14).

$$\lambda = \left(\frac{3k}{E_{\mathrm{cm}}h^3}\right)^{0.25} \tag{14}$$

The most common method of modelling the arrangement of the distributed load is the block method, where the minimum and maximum moments are determined with the modification of the ratio of the loaded and unloaded parts of the industrial floor. According to the formula of Hetenyi, the maximum positive and maximum negative moments will act according to figure 1 with a loading area of $\pi/2\lambda$ and π/λ, respectively, according to Fig. 1.

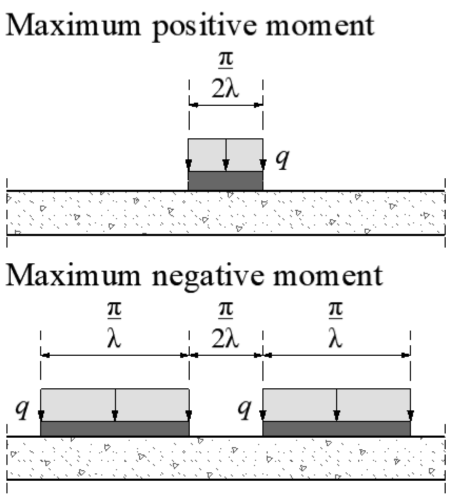

Fig. 1 Maximum moments in the case of distributed loads.

The maximum distributed load can be calculated with the following formula:

$$q = 5.95\lambda^2 M_{\mathrm{n}} \tag{15}$$

where M_{n} is according to Eq. (2).

Some important notes to the design of distributed load: first of all, it is important to clarify that the formulas are based on the linear material model, so the reinforcement (fibre or steel bar reinforcement) has no effect on the result. Because of this only plain concrete industrial floor can be designed for distributed load until the appearance of the first crack. Due to this efficiency will be low, the solution will be uneconomical. The guideline is aware of this and tries to correct this in a way that decreases the safety factor in the case of distributed loads, saying that the concrete material also has the safety factor included. This approach is completely wrong and is against the partial safety factor method of Eurocode. Moreover, it is important to note that the formula assumes infinite slab, so the joints and their effects are not taken into account. When the arrangement of distributed load extends beyond the joints the formula will give an incorrect result, since calculating with the joint as a hinge will result in a favourable situation. And finally, the formulas of TR34 for defined position of distributed load are inaccurate, which are needed to be revised and/or restricted.

5. Difference between Linear and Non-linear Finite Element Methods

Most of the finite element software that can be found in every engineer's office contains material models for designing concrete structures. However, these material models can only follow the behaviour of the structure with proper accuracy until the appearance of the first crack, as the function describing material behaviour consists of one straight line with both ends being stress-strain pairs belonging to tension and compression failure. With such material models reinforcement in the concrete can not be considered, as the concrete is still in an uncracked state and there are no cracks on it, so the reinforcement works in a limited way in the structure. Most similar software is able to define the amount of necessary reinforcement, but this is only based on the stress in the concrete and the surplus stress of the reinforcement. Software with such material models is called software capable of linear design. Typically, this software offers the opportunity of running a non-linear design, which can be misleading, but this non-linearity only appears on the geometric level (initial eccentricity, equilibrium of deformed shape, etc.), and not in the functions describing material behaviour.

Advanced finite element software (ABAQUS, ANSYS, ATENA, DIANA) has material models describing non-linear behaviour, moreover in most of them the user can provide his own material model as an individual function to the structure wished to be analysed. After the crack the hardening and softening behaviour can be modelled with non-linear material model. As an example a non-linear material model can be a steel material model considering hardening.

6. Advanced Material Model for Concrete

The basis of modelling concrete with advanced finite element is that the applied material model is able to manage the different behaviours of concrete to tension and compression. This condition is not even possible in most cases of the above-mentioned software able to manage nonlinear material models, programmes designed specifically for concrete structures are required to be used (ATENA, DIANA). A proper tool for modelling concrete structures can be a material model applying combined failure surface, which applies failure surface of William-Menétrey for compression and Rankine for tension. Several failure surface pairs can be found in literature, which can be suitable for modelling concrete structures (Von-Misses and Rankine; Drucker-Prager and Rankine), although the best approximation was provided by the above-mentioned William-Menétrey failure surface [8]. The most advanced finite element software is able to display the discrete cracks, as well as calculating the crack widths. For this the value of the characteristic length is required to be defined, which connects diagrams of concrete stress-strain and stress-crack width. The greatest advantage of advanced finite element calculation is the display of crack propagation. With this software it is possible for the users to define functions describing material behaviour, which opens the door for verifying experiments and modelling special materials as well.

For modelling and designing industrial floor it is necessary to be able to model the reinforcement as well.

Most frequently there is a possibility to model discrete reinforcement in this special software, which means that reinforcement bars are placed in the 3D material model as a link element. This provides an opportunity to model their real behaviour and also to optimise the structure.

Most often industrial floors use steel- or macro-synthetic fibre reinforcement, which can also be modelled in this advanced finite element software. The two most common methods are discrete modelling of the fibres and the modification of the fracture energy of the concrete. While the former is typically more common in research models, then the modified fracture energy method works well in practice too for modelling fibre reinforced concrete structures. The essence of the method is modifying fracture energy of the concrete by added fracture energy of fibre reinforcement (Fig. 2). This value is different in the case of each fibre type and dosage, calculation of these values is possible by inverse analysis carried out in laboratory experiments. This method is suggested for modelling fibre reinforced concrete tunnels by the ITATech International Tunnel Association [9] as well.

There is a possibility to define additional time dependent material models, by which hardening of the concrete can be modelled after pouring, therefore the appearance of the initial shrinkage crack can be considered during design. This material model follows the timely changes of the main material parameters (elastic modulus, tension and compression strength), thus compares the stress in the structure with different material parameters in each calculation stage. With the help of this the size of the slabs which do not have shrinkage cracks on the surface of the floor can be defined. During calculation the effect of the shrinkage compensating admixtures can also be taken into consideration during defining parameters of the material and determining the maximum loads.

7. Numerical Model of the Structure

The first step of finite element modelling of the floor is providing proper geometry for the software, which gives the most realistic results. The soil below the industrial floor, the concrete floor and its reinforcement itself and modelling certain load bearing slabs are equally important. Different parts of the floor (saw-cut joints, dowels, edges) require separate models; this is the only way to be certain that

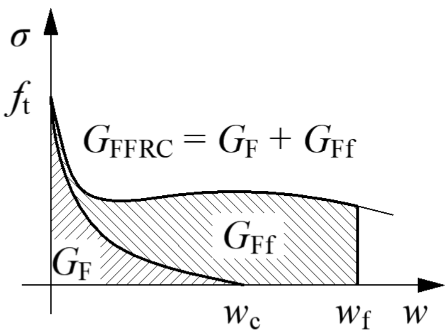

Fig. 2 Fracture energy of concrete and fibre reinforced concrete, and added fracture energy.

our structure is capable of the necessary load bearing capacity in all of its parts.

Subgrade modelling offers multiple methods. While in one of them the soil is built as a separate material model with material models describing proper soils (Drucker-Prager or Mohr-Coulomb material model), then there is a simpler, but similarly precise method with less calculation time, which is modelling the soil by a nonlinear spring. In this case the rigidity of the spring substituting the soil must be set so that it provides the real load bearing capacity of the soil to compression, while it has a close to zero load bearing capacity to tension.

These springs defined in this way are under the industrial floor. It is advisable to carry out the design in a three-dimensional model so that the spatial stress state can develop properly, as well as the complex load situations can only be followed this way.

Finite elements are hexahedra elements with 20 nodes, which can properly follow spatial movement of the structure as well as spreading of the cracks. At least four finite element lines are required to be placed along its depth, as this is the certain way to properly follow flexural stresses. As running time of the calculation depends on the number of finite elements, it is advisable to take advantage of the symmetry of the structure if it is possible, which allows modelling only the half (in case of single symmetry) or the quarter (in case of double symmetry) of the geometry of the structure as sufficient. Upon defining geometry, it is important to use the proper additional support if needed. There is an opportunity to place point, line and surface supports as well in the software.

A typical FE (finite element) model of an industrial floor can be seen in Fig. 3.

8. Defining Loads and Actions

In the finite element software it is possible to define different loads and actions, such as structural loads, displacement or thermal actions. Typically, the industrial floors need to be designed for structural loads. Considering their dimensions these loads can be point loads (shelf leg load, wheel load), line loads (crane rails) and distributed loads (stored materials, containers).

Special loaded floors can also be modelled by finite element software, for instance the floors of cold storage units or floors that are exposed to sunlight (thermal load). In this case the software allows linear changing of the thermal load, by which it can be considered that the upper layers are getting colder/hotter than layers closer to the subbase. As mentioned before there is also a possibility to model the shrinkage of the concrete, which can be significant in the initial stages of the floor.

When discussing special loads, it is certainly substantial to mention load by fire. Similarly to the shrinkage model it is possible to define a material model dependent on temperature by the finite element software, which can consider the decrease of concrete parameters as an effect to the increase in temperature. Besides the above listed opportunities, it is also possible to consider creeping of concrete, corrosion of reinforcing steel and the deterioration of bond of reinforcing steel.

During finite-element design dynamic and fatigue loads can also be modelled besides static load. In the case of dynamic load, the speed of load transmission can be modelled. Fatigue design is of key importance for concrete structures if frequency of the load is high, such as floors of storage halls with regular moving, or floors with the rail of an industrial crane. In this case there is an opportunity to decide with finite element simulation whether the floor can withstand the load cycle that can be even several million occasions, as well as defining how many cycles it takes until failure. With these kinds of calculations it is possible to carry out a life cycle design as well.

9. Comparison with Laboratory Experiments

There are a relatively few real size laboratory tests

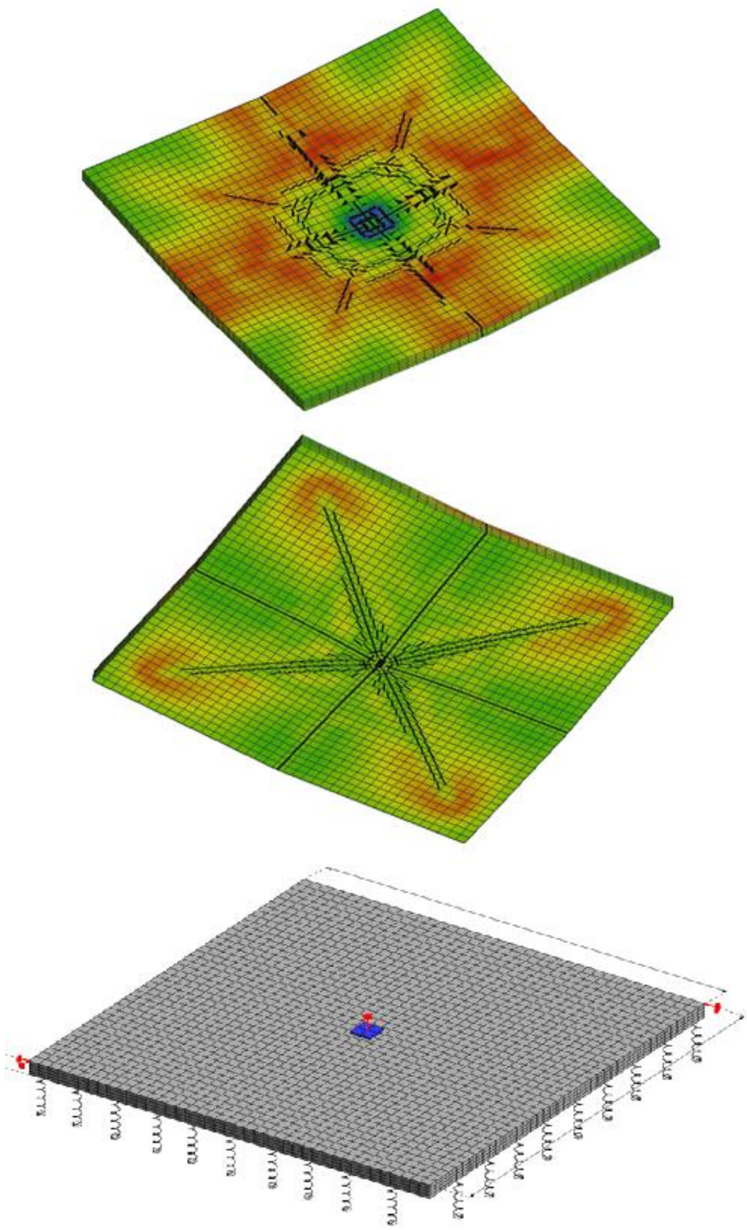

Fig. 3 Crack propagation and FE model of an industrial floor with a point load in the middle.

of industrial floors that can be found in literature, which is probably caused by the large laboratory space requirement and the complexity of the testing itself.

An industrial floor was tested by a middle point load and the results of the test were measured until failure [10]. This load bearing capacity was also calculated with the help of guidelines and different types of FEA. The correlation of the results can be seen in Fig. 4.

It can be clearly seen that the analytical results are much lower than the actual load bearing capacity, these results include big safety. Finite element designs of Falkner [11] and Shentu [12] are not far from the real test results, however, they defined a higher load bearing value than the actual load bearing capacity, so the approximation is not in favour of safety. The material model developed in ATENA [8] provides a

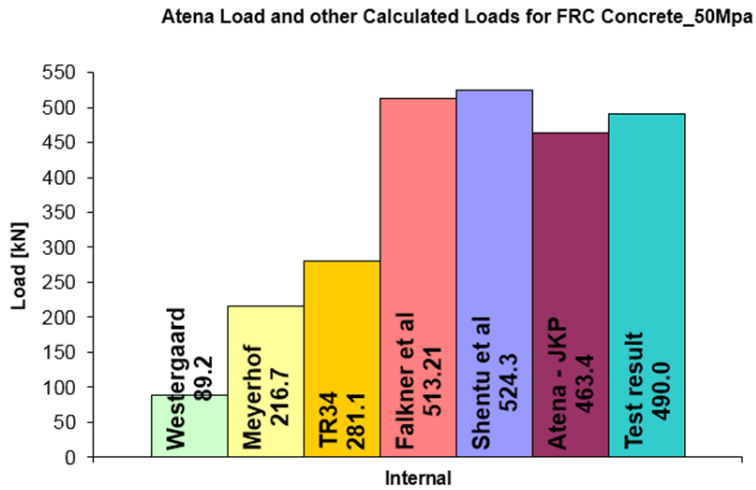

Fig. 4 Comparison of the laboratory test and different analytical and numerical results.

good approximation to the actual load bearing capacity of the floor and still on the safe side.

On the basis of these data, it can be confirmed that it is possible to provide a good approximation to the load bearing capacity of the floor with the help of finite element software, the formulas defined by the guidelines are only able to define peak load of the industrial floor with significant safety.

10. International References

The design of several international projects was made by the above-mentioned method. In many cases the complex load arrangement or varying floor thickness interfered with applying guidelines, thus in these cases the designs were carried out by using finite element software. It also occurred on several occasions that the load bearing capacity of an already finished industrial floor needed to be defined afterwards, due to the changing functions of the warehouse. These instances required load values quite close to reality, as this was the only way the investment would happen. The use of finite element software became an inevitable necessity as the conservative calculation method of guidelines had significant safety.

A great example for applying the design method in Hungary is the roller skate park of Gödöllő, where due to the strict conditions on cracks and the complex geometry it was required to use the finite element method [13].

11. Summary

This article presented the traditional analytical design method and also an advanced finite element design of concrete industrial floors. With the help of the analytical model a quick calculation can be made for industrial floors, but it has its limits, and is also working with serious assumptions. The finite element design can be a requirement in cases where geometry or arrangement of the loads is complex, so the design can not be carried out by the traditional formulas of guidelines. In addition, this method is also suitable for revising and reinforcing the already constructed floors that were designed or constructed with mistakes. By analysing the crack propagation, it is possible to determine the reason for the cracking of the floor. It is important to mention that reinforced concrete slabs (by reinforced concrete, welded mesh or some type of fibre reinforcement) can only be designed precisely with finite element software with nonlinear concrete material model; software used daily for structural design (AXIS, FemDESIGN) is not suitable for this. Applying the advanced finite element method requires an equally advanced computer background, as well as the engineers, who should be in possession of complex finite element method knowledge for the values to be set properly. Regardless of the above-mentioned advantages and disadvantages, currently this method can be applied for special industrial floor designs, while in the future it is expected to be even more popular.

Acknowledgements

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