Journal of International Scientific Publications: Materials, Methods and Technologies
Volume 8, ISSN 1314-7269 (Online), Published at: http://www.scientific-publications.net

METHODS OF COMPARISON STEEL AND REINFORCED CONCRETE STRUCTURE'S ON EXAMPLE OF A ONE-STOREY, SINGLE-SPAN FRAME

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Abstract

In the civil engineering practice, there are many ways of completing construction investment projects. Each construction can be built in a number of ways, which enables architects and designers to prepare different variants of planned buildings. Selection of a technology employed to raise a building object is one of the most important decisions to be made while planning an investment project. The problem has been presented on a model of frame with full columns and a mono-pitch spandrel beam with the solid cross-section, made as a steel and monolithic reinforce concrete construction.

Key words: *analysis of construction projects, managing a construction project, comparisons of the structures*

1. INTRODUCTION

In engineering practice we have an opportunity to choose between different technologies of construction works and between different materials (Giżejowski et al. 2010).. Wishing to achieve economically satisfying solutions while meeting all other requirements that building constructions should fulfill, comprehensive analyses are made, based on different selection criteria. The fundamental requirements most often comprise:

- reliability of the construction and its useful life,
- technological criteria, which depend on the used materials, machines, production processes, availability and the possibility to transport materials and construction elements to the construction site,
- functionality of the building, depending on its size and specific features,
- economic criteria, which define the costs indices, especially the costs of construction works, the maintenance costs once it is erected, consumption of materials, total weight, share of industrialized solutions in the construction process, durability and value of materials recovered once the useful life of a building is over,
- legal considerations, imposed by the law binding in the area where a given building investment is planned and executed,
- formal issues, such as imposed norms and standards,
- ergonomic and esthetic problems, to which investors and future users of the building pay special attention,
- ecological questions, regarding the impact of an erected construction on the surrounding natural environment (Tarnowski 1997)

While checking off the above criteria, it is important to bear in mind that the reliability and safe use of a building object are two essential objectives. A construction which fails to satisfy these conditions is automatically discarded. Having to fulfill all the above conditions, a designer faces an immense challenge. Apart from knowing the fundamental design rules and principles, they should also be familiar with the current construction market, the latest technological solutions and possible future developments so as to be able to justify the choices they make for a given construction design (Bentz , Collin 2004),. This article discusses comparative analytical methods applied to analyze variant construction solutions, using as a case a choice between a steel and ferroconcrete one-story single-span frame with full columns and a mono-pitch spandrel beam (Ajdukiewicz 2011).

2. DESCRIPTION OF A MODEL CONSTRUCTION

A model of a one-storey, single-span frame with full-walled columns and a mono-pitch spandrel beam with a full and solid cross-section along its entire length, bearing a uniform bracing load of the roof structure and external

forces applied to the roof and the walls (Grabiec et al. 2001). For comparison, it was assumed that the construction would be made of steel and of reinforced concrete. In the presented case, for both the steel and the reinforced concrete constructions, it was necessary to assume that all joints are rigid because such is the type of joint made in a monolithic construction. The following basic parameters were assumed:

- a variable span length, that is the centre to centre span between opposite columns,

- a fixed longitudinal span of the frames,

- a fixed slope of the spandrel beam, and consequently variable heights of columns with the variable span and constant height of the construction.

The described construction is composed of the columns and the spandrel beam. With the assumed work of the construction, the horizontal elements are subjected to bending and shearing. In the ferroconcrete construction, the centre to centre span was determined depending on the adopted conditions, with the adequate dimensions typically smaller than 25% of the span of symmetrically reinforced beams; when designing the steel spandrel, HEB I-beams were used. The described structure rests on columns anchored in foundation bases whose height depends on the roof slope angle. The columns are the main elements exposed to compression and transfer all forces to elements of the foundation. Same as in the case of horizontal elements, the dimension of the centre to centre transverse section of a ferroconcrete construction oscillate within a quarter of the span, and the reinforcement is symmetrical; in the steel construction, it is made of I-beams. Figure 1 shows a design of the construction.

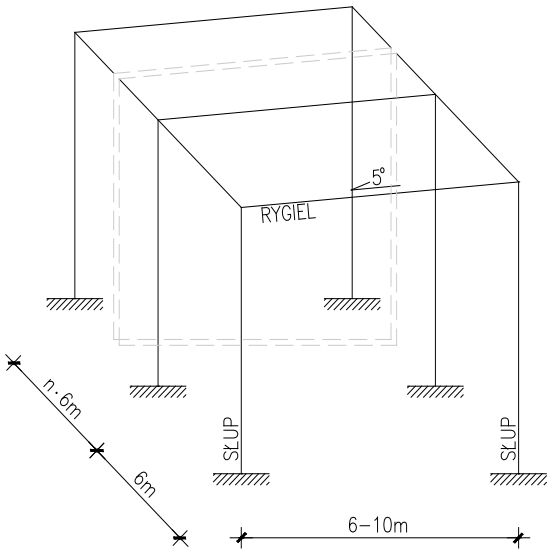


Fig. 1. Computational design of the analyzed construction, *Source; the author*

The following construction was taken for the calculations: a middle flat frame of a single-span hall with an inclined spandrel beam and a constant slope angle of the roof equal 5^{o}, with the constant height at the highest point of the intersection of the column and spandrel beam equal 6 m and the longitudinal centre to centre span of the frames equal 6 m. The transverse distance between the columns will be variable, from 6 m to 18 m at 2-m intervals. The analyzed building will stand in the IV snow zone and I wind zone according to the Polish standard. The external columns are exposed only to wind, assuming the walls are cased. The length of the hall was assumed to equal n x 6 m, as the analysis comprises only the middle frame and an infinite length of the building affects only the wind load calculation, which simplifies its value to a constant for different widths of the aisle in the particular variants. Below, results of solutions for individual sets of frames are presented in the form of the most optimal – with respect to their strength - steel and reinforced concrete cross-sections for particular elements of the frame, which will serve as a data base for further economic and technical considerations. In the table, depending on the span of the aisle, cross-sections of spandrel beams and columns are divided, but the latter are considered identical in each case, be it the right or the left column.

3. TRADITIONAL METHODS OF ANALYZING BUILDING STRUCTURES

Among the basic traditional methods is an approach in which parameters of the consumption of materials and unit costs are calculated and juxtaposed. The first is the ratio of the volume of reinforced concrete to steel, in appropriate standard units, used in a given structure (Górski, Hojarczyk 1970).

$$Z = [m^3]\ reinforced\ concrete\ /\ [t]steel \qquad [1]$$

It reflects the ratio of variant consumption of individual materials to erect the same building object, e.g. when a steel structure is chosen, and the used material equals 10 kg per the cubic capacity of the building, or when 0.05 m^3 of reinforced concrete is used, the parameter is equal 5. A reverse equivalent would be the quotient of the unit prices of compared materials.

$$N = \frac{unit - price - of - ferroconcrete - structure}{unit - price - of - steel - structure} \qquad [2]$$

The results of this simple analysis is the product of the above parameters. If the Z x N quotient is more than one, then the steel structure in the analyzed building object is less expensive in terms of used materials. Such comparisons can also be made with respect to other outlays, such as engaged equipment or labour (Górski, Hojarczyk 1970) While analyzing potential applicability of the above method, it appears than we can compare structures of a given function built from suitable materials, by comparing weights and strength characteristics of different types of steel or concrete. For example, a compressed element made of steel or concrete, it is possible to derive a formula for Z equivalent:

- assuming that elements achieve maximum strength, we transform the formula for the strength of a section submitted to with concentrated force.

$$\frac{Q}{A} = f_d \qquad [3]$$

$V^b = \frac{Q \cdot L}{f_d^b}$ - in the case of concrete, we need the volume used in the analyzed element

$G^s = \frac{Q \cdot L \cdot \gamma^s}{f_d^s}$ - in the case of steel, we need the used weight

where: Q - force compressing the element,

A - cross-section of the element,

f_d - calculated compression strength (f_d^b for the concrete and f_d^s for the steel element),

L - length of the element,

V^b - volume of the concrete element,

G^s - weight of the steel element,

γ^s - volumetric density of steel.

- If we assume in the above formulas that the product Q · L is the same in both cases, we arrive at the final formula to calculate equivalent Z

$$Z = \frac{V^b}{G^s} = \frac{1}{f_d^b} \cdot \frac{f_d^s}{\gamma^s} \qquad [4]$$

Below, in table 1 we present examples of Z equivalents for some classes of concrete and types of steel, which visualize the difference originating from properties of given materials in the analyzed work of a compressed cross-section.

Tab. 1. The comparative index Z of reinforced concrete and steel for a compressed element *

Stael / Concrete	f_d^b [MPa]	S185	S235JR	S275JR	S355J2
f_d^s [MPa]		165	205	225	295
C16/20	11,43	1,84	2,29	2,51	3,29
C25/30	17,86	1,18	1,46	1,61	2,10
C50/60	35,71	0,59	0,73	0,80	1,05
C80/95	57,14	0,37	0,46	0,50	0,66

* results in the table were computed for the steel volumetric density equal 7850kg/m^3

Source: the author

Naturally, the results in the table are approximations of actual results. However, although they lack the ideal precision of calculations, this method of comparisons generates reliable results and can serve as a preliminary evaluation of a planned construction, assuming that same load capacity of the structures made from different materials is ensured. Another methods (Górski, Hojarczyk 1970). to compare costs of structures built from different materials is the one where the costs ration index is calculated for assembled constructions made from different materials:

$$\psi = \frac{a}{c \cdot S}[n \cdot c + p \cdot c(S-1)] = \frac{a[n + p(S-1)]}{S} \qquad [5]$$

where:

$a = \frac{G_i}{G_{i+1}}$ - expressed the proportion of weights of structures made from ith material,

$S = \frac{c + w + m}{c}$ - is the ratio of the total costs of a unit quantity of the first material (c),

workshop labour (w) and costs of assembling (m) elements to the costs of material as such

$p = \frac{w_i + m_i}{w_{i+1} + m_{i+1}}$ - expresses the ratio of workshop labour (w) and assembly costs (m) of the ith material,

$n = \frac{c_i}{c_{i+1}}$ - expresses the proportion of costs of ith materials.

The above method does not include maintenance costs, which may differ from one structure to another, but for the sake of our subsequent considerations, it was assumed that this type of comparison will suffice to describe the set target of the analysis.

4. MODERN METHODS OF ANALYSIS OF COMPARATIVE CONSTRUCTIONS

In modern engineering practice in the analysis of the structure often are presented other aspects than it once was. Currently, the greatest emphasis is placed on the broad sense an economy. Such areas as consumption of materials, time of construction works and associated costs of construction are being increasingly important (Saaty 1990).

4.1. Consumption of materials and technology

Nowadays, when planning investment projects, much emphasize is laid on the use of materials. This tendency is congruent with the ecological approach to the construction industry, saving raw materials, decreasing the transportation load and ensuring that the investor can attain financial savings.

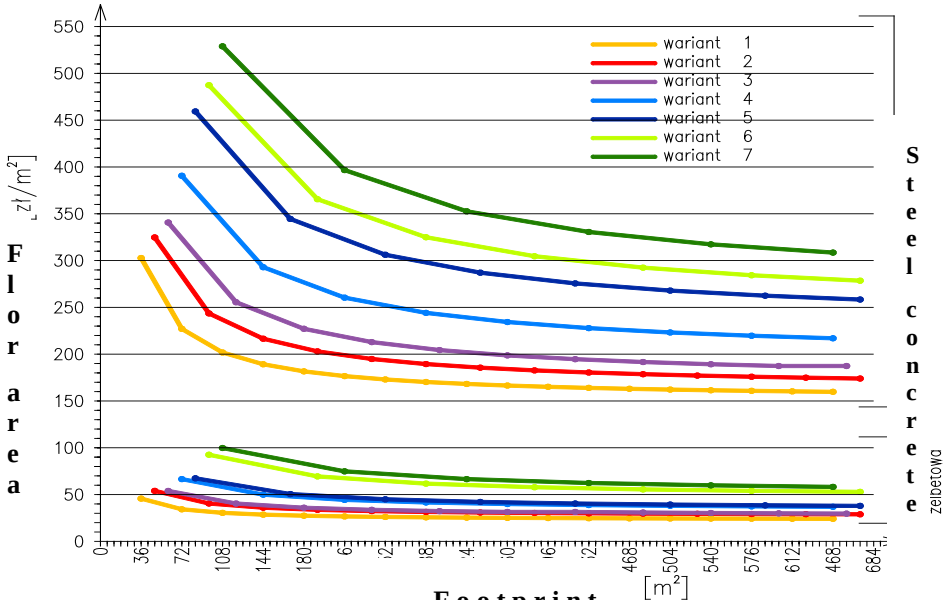


Fig. 2. Cost of used material per 1 m^2 of the floor area of a building depending on the footprint

Source: the author

The diagram illustrating dependences between costs of materials and footprint has been drafted based on the author's own calculations. The diagram shows an evident advantage of a ferroconcrete structure over a steel one.

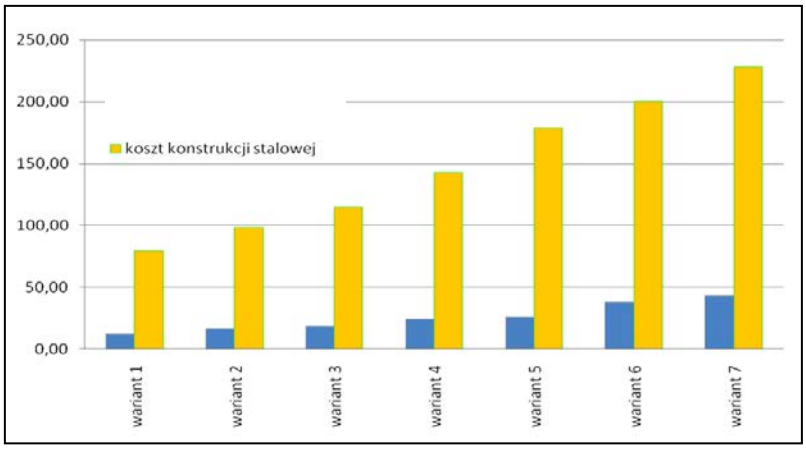


Fig. 3. Comparison of costs of used materials per 1m^2 of the surface of walls in particular variants

Source: the author

It may seem futile to analyze relationships between the consumption of materials and the building's cubic capacity, having examined the its relation to the footprint. And actually many designers will think so. However, we should know that the cubic capacity of a building may change depending on a variety of parameters. The

simplest ones, usually stemming from the applied technology, are the footprint at the constant height of aisles, variable height at the constant floor area and changeable dimensions of a hall only at certain points long- or sidewise.

The analyzed models are simple halls, which is why the question of the unification of elements will not be considered. We will discuss, however, the effect of the surface of encasement to thee costs of used materials per structure, provided the same system of building the walls. All that needs to be done is to compare frames of the spans presented before to the lateral surfaces alone, and owing to their proportional increase as the length of the hall increases, they can be analyzed in the same way as for a single-span hall.

The total costs of encasing the building will decrease proportionally to the decreasing cubic capacity of the hall, which means the decreasing size of vertical surfaces. However, let us focus on the analyzed variants, which we compare with respect to their unit encasement surfaces. It should be added that the total surface is different for each variant due to the changing widths of spans. In such comparison, as in the above point, the reinforced concrete structure is the most economical solution in terms of the consumption of materials. Comparing halls with the same cubic capacity and footprint, and consequently with the same costs of building outside walls, building objects raised from steel will be a more expensive variant with respect to the costs of materials (Pawłowicz et al.2011).

4.2. Time of construction works

Another important criterion helping to choose the best solution is the time it will take to construct a given building. Each day at a construction site incurs huge costs, due to the labour done by people and machines. The presented analysis is based on generally accepted time standards determined according to the current behaviour on the market. When conducting such analysis, it is advisable to pay attention technologies employed in order to execute the analyzed variants. As assumed before, the reinforced concrete frames will be made on the site, as monolithic structures, while the steel ones will be raised from prefabricated elements made in a factory. The works required to make ferroconcrete frames include: reinforcement with steel rods (main, transverse and additional reinforcement), making pole scaffold and formwork under the spandrel beam, curing of concrete. We should also add the time needed to make cement, but in the case analyzed herein we assumed that ready-made cement will be delivered from a cement plant (Szafranko 1997).

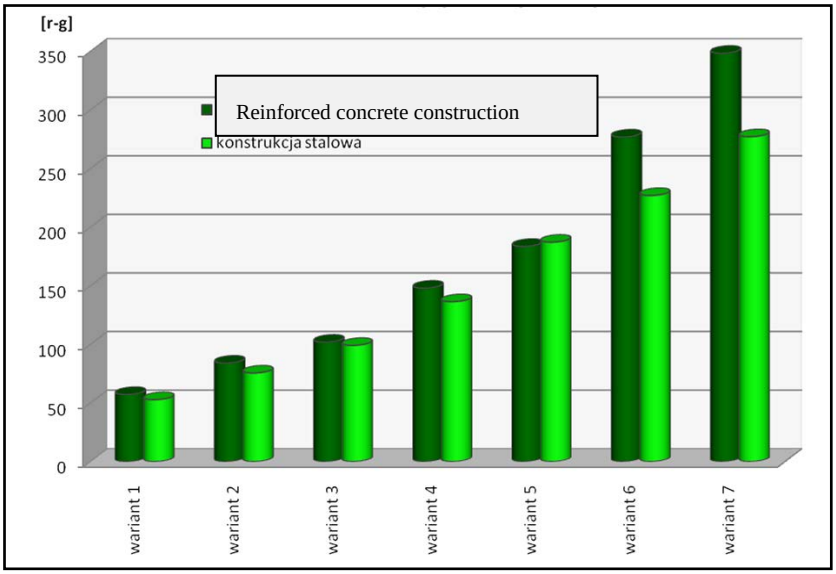


Fig. 5. Comparison of the time needed to build a ferroconcrete and steel structure in particular variants

Source: the author

The works which must be included in an analysis of a steel structure assembled at the beginning are the assembly of elements delivered from a plant and covered with priming paint, and then painting the whole structure on the construction site. A quick look will be enough to see how much the two technologies differ from each other,

although they are used to erect seemingly similar building objects. The monolithic structure involves much more complicated works, strongly dependent on numerous external conditions, which has an evident influence on the eventual duration of construction works.

The diagram illustrates differences in the time it takes to produce one frame in either of the two variants. The numbers corresponding to working hours needed to make elements of the building object oscillate within 53 to 277, which means that the work time extent by 32-50 hours for each 2-meter increase of the frame's span. Eventually, the change of the span between the columns reaching the maximum planned distance causes an increase in the duration of the construction works by as much as 80%. The increasing tendencies are similar in character for both analyzed technologies, and the steel construction is obviously much better than the reinforced concrete one, which takes much longer to make.

4.3. Resistance of constructions to corrosion and fire

Another issue that needs to be considered is the resistance of a construction to unfavourable environmental conditions, substances causing corrosion and high temperature that occurs during a fire. Typically, building standards help us classify individual elements and describe the characteristics they should demonstrate under such circumstances (González et al.1995).

All constructions should be as fireproof as possible, which means they should retain their functions during a fire. The recommendations contained in the national guidelines aim at preserving the stability of whole constructions as well as their elements for a set time depending on their class. Another aim is to ensure that further spreading of a fire or smoke, as well as a risk of ignition will be controlled, and the construction will behave in a way that will enable and facilitate fie rescue and escape actions. These conditions are considered in the context of materials used for making whole constructions or their constituent parts, and their interactions during a fire. The two analyzed model constructions belong to non-flammable materials with low smoke emission. Classification of elements depends on two aspects: the criteria and the time during which these criteria must be met. The classification of each element must be determined during the design stage so as to envisage ways of additional, external fire control. The main reason why this is so important to analyze tolerance of constructions to fires is that under high temperatures materials automatically lose resistance. Steel has many advantageous characteristics, but is very sensitive to high temperatures. All steel constructions are typically given fireproof protection, without which they will not last longer than half an hour. The problem is less serious in the case of reinforced concrete structures, but cannot be neglected altogether. Reinforced concrete contains steel elements, which perform an important function in the behaviour of ferroconcrete constructions.

When it comes to protection of ferroconcrete structures, the solution is simple. In order to provide all elements with a desired fireproof class, minimum dimensions of cross-sections and an adequate thickness of concrete cover for the reinforcement are designed. This is usually the only and sufficient method to protect newly raised constructions. Sometimes, however, dimensions of particular elements are limited by technological or architectural demands, which is when other methods must be deployed. These most frequently are: thick-layer covers such as fireclay mortar sprayed directly over the construction, analogously to steel structures. Other systems applied to steel constructions are not suitable to protect ferroconcrete structures from fire (Bentz, Collin 2004).

Resistance to corrosion is different for different materials, and therefore there are different anti-corrosion solutions. Regarding steel, which is used in both systems, corrosion is caused by formation of different salts on the surface of a steel element due to reaction of elements from the metal with other elements. Anti-corrosion methods include prevention of moisture and water collection by giving appropriate shapes to the elements and whole structures, or by reducing their emission when using the building, or by avoiding direct contact between unprotected steel with materials having different electro-chemical potential, e.g. aluminum. However, by being so vulnerable to the effects of external conditions, this material needs additional protective actions. They include two basic forms: paint layers and galvanizing.

These are unnecessary in ferroconcrete constructions because the concrete itself functions as a protective cover. Attention should be paid, however, to the width of gaps and thickness of concrete cover, which are regulated by norms and depend on the environment. According to the European norms, exposition classes are represented by the letter X and, depending on the environment, the number 0 when corrosion risk is absent, C – damage caused by carbonization, D – corrosion due to chlorides, S – effects of chlorides from seawater, F – elements exposed to cyclic freezing and thawing, and A – under chemical effect. Layers of concrete cover also depend on the class of applied cement and the number of checks carried out. The question of scratches is usually solved during the designing stage, by selecting adequate cross-sections of elements and amount of reinforcement.

Considering the above information, it can be concluded that anti-corrosive protection is similar to the ways of ensuring tolerance to high temperatures. Thus, steel constructions require use of different protection systems, while corrosion of ferroconcrete structures is prevented at the design stage by providing sufficiently thick concrete cover. Because the fireproof and anti-corrosive coatings on steel components can be combined, they were not analyzed separately, because the costs of painting steel surfaces would be similar. On the other hand, in our analysis of monolithic structures, the thickness of concrete cover was considered simultaneously regarding the unfavourable influence of the surroundings and an event of a fire.

4.4. Use of the construction

The major financial outlays which an investor must incur during the construction process should be amended by adding the costs needed to use and maintain a ready building object. Beside typical costs caused by maintenance, on a more or less same level each year, the analyzed model structures need periodic checks and repairs (Wei-Wen , Winter. 1960).

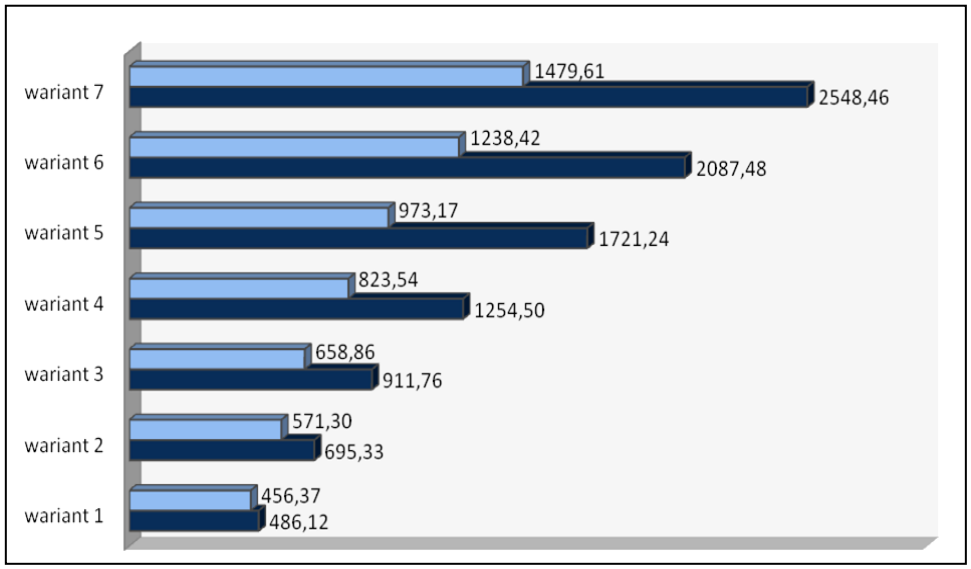


Fig. 8. Costs of renovating one steel and ferroconcrete frame after 10 years, for each of the span variants; *Source: the author*

The diagram in figure 8 shows differences in costs of renovation of the model solutions. With smaller spans, these costs are similar in both types of constructions, but as the span increases, the difference reaches 42%. In each variant, the financial inputs on renovation are higher in the case of a steel structure, and differ by 6% to 42% from analogous reinforced constructions. Regarding both types of solutions in the variant with the maximum transverse span of columns, the difference rise by 81% and 69%, respectively. It is also possible to refer the calculated values to 1 m^2 of renovated surfaces. These data are included in the table 2, below.

Tab. 2. Specification of costs of renovating 1 m^2 of steel and ferroconcrete constructions

No of variant	Steel construction			Ferroconcrete construction		
	Total cost of renovation [PLN]	Area submitted to renovation [m^2]	Cost of renovation of 1m^2 [PLN]	Total cost of renovation [PLN]	Area submitted to renovation [m^2]	Cost of renovation of 1m^2 [PLN]
1	486,12	15,38	31,60	456,37	20,45	22,31
2	695,33	20,10	34,59	571,30	25,61	
3	911,76	24,35	37,45	658,86	29,53	
4	1254,50	30,54	41,08	823,54	36,91	
5	1721,24	38,93	44,21	973,17	43,62	
6	2087,48	44,96	46,43	1238,42	55,50	
7	2548,46	51,89	49,11	1479,61	66,31	

Source: the author

The data contained in the table verify the commonly accepted claim that reinforced concrete constructions are much more durable and under normal exploitation conditions do not require any major repairs during the planned usability life.

4.5. Costs of making the constructions

The total costs of constructions consist of various components. Out of the ones discussed above, the given specification contains costs of erecting the construction, costs of renovation and maintenance and costs of anti-corrosive and fireproof protection.

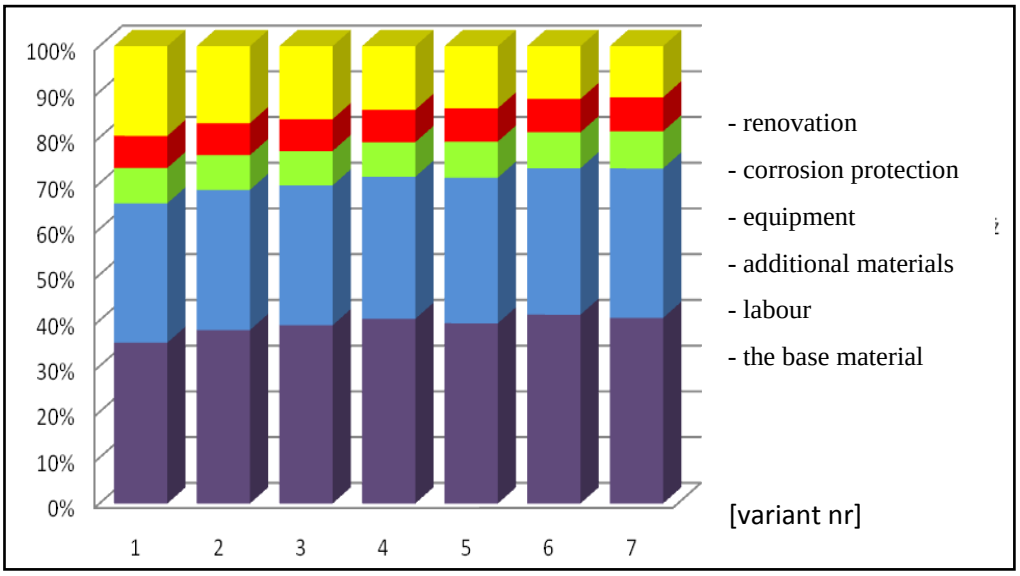


Fig. 9. Contribution of particular costs of building and using a a single ferroconcrete frame in particular span size variants Source*: the author*

In ferroconcrete constructions, the highest share to the total costs is contributed by the main construction material and labour – these costs are similar in all variants. The protection of a construction against corrosion or fire is minimal, almost negligible, which implies that it is very hardy to external environmental factors.

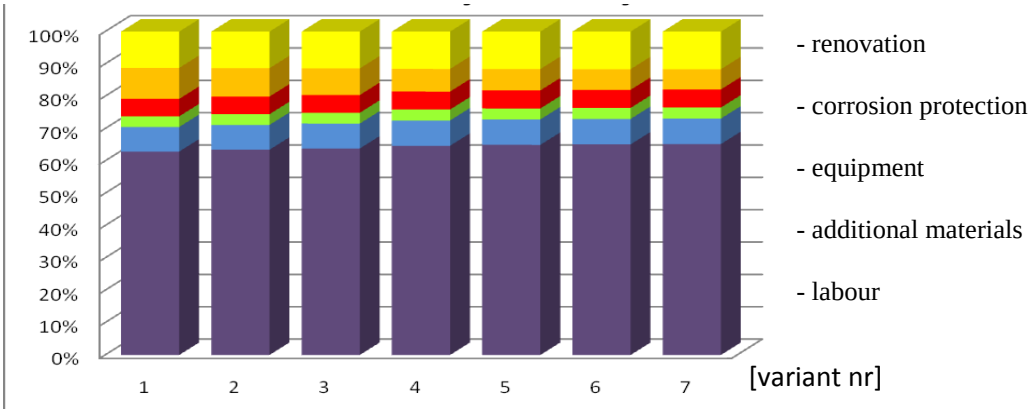


Fig. 10. Share of individual types of costs of building and using a single steel frame in particular span size variants Source*: the author*

Fig.10 shows a very high share of basic construction material in the total costs of erecting and maintaining a steel structure. Steel as a building material is very expensive. Also, notable is a higher percentage of costs of renovation and protection than in the case of ferroconcrete constructions. The other cost components are similar in both cases and do not increase notably as the span increases.

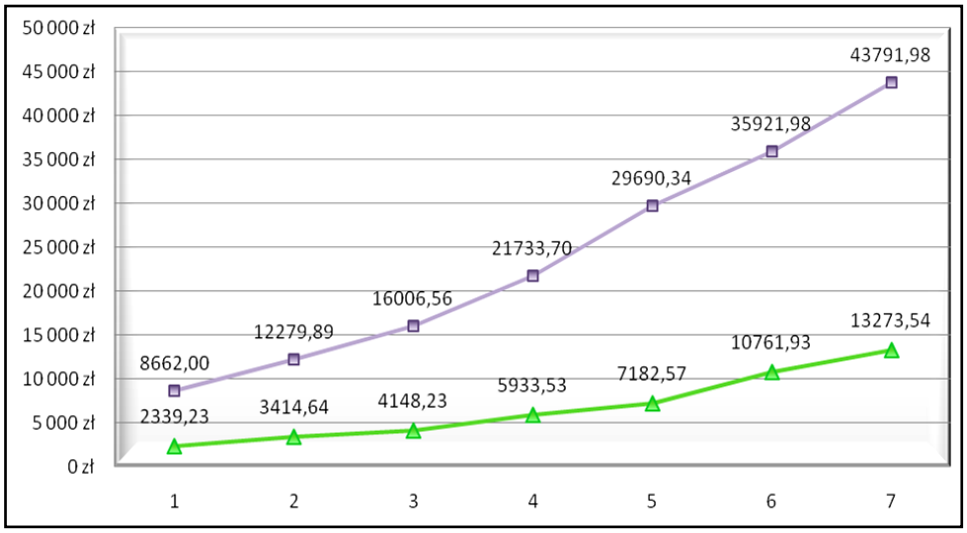


Fig. 11. Total costs of building and using a ferroconcrete frame and a steel frame relative to one frame in each variant *Source: the author*

The diagram in fig. 11 confirms our previous observations. Having analyzed all the variants, we can conclude that ferroconcrete constructions are a much more economical solution. Although the differences are small for constructions with smaller spans, it would be uneconomical to choose a steel construction when the span between columns is 18 m, as this solution is 70% more expensive.

Tab. 3. Main advantages and disadvantages of steel and ferroconcrete constructions

Ferroconcrete construction	Steel construction
– advantages – -low costs of making and maintaining – -small errors while building are reparable at relatively low cost, – disadvantages – -long time to build, – -the multi-component element sensitive to changes in loading direction, – -large deviations of dimensions of elements, – -difficulty in reproducing design assumptions, – -much labour inputs to build, – -many factors calling for care and attention on a construction site, – -costly reinforcements of the construction, – the construction cannot be disassembled, – -the material is practically unrecoverable, – -large weight of the whole construction, – -cross-sections of elements diminish the usable floor surface and cubic capacity, -difficulties during the assembly of installations inside the building.	– disadvantages – -high costs of making and maintenance, – -each, even the smallest mistake causes serious consequences, – advantages – -relatively short time to build, – -the isotropic material resistant to changes in loading direction, – -small deviations in dimensions of elements, – -ease of reproducing design assumptions, – -few activities that require control on a construction site, – -quite simple and inexpensive ways to reinforce the construction, – -possible disassembly of the construction, – -the material can be recovered, – -relatively light constructions, – - cross-sections of elements need not decrease the usable floor area or cubic capacity, – -easy to assemble installations in the building.

Source: the author

5. CONCLUSIONS

In the civil engineering practice, there are many ways of completing construction investment projects. Each construction can be built in a number of ways, which enables architects and designers to prepare different variants of planned buildings. The requirements set in front of building constructions, described above, show how wide is the range of analyses concerning the discussed solutions. The model construction can be made as a steel or monolithic ferroconcrete structure. The description of the construction given in this article demonstrates how differently the individual criteria are satisfied by the two technological variants. The table 3 juxtaposes other aspects, which cannot be compared otherwise, for example as diagrams, because they are not mathematically comparable. The red colour highlights advantages.

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