The design of steel constructions in seismic conditions

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Abstract. In this article, the principles of designing of seismic resistant steel frames of industrial buildings are considered. The particular attention is paid to the damage causes of the steel frames under the seismic loads affects, and to the requirements that must be considered while designing the steel frames in seismically active areas. The most suitable materials that can be used to strengthen the steel frames have been studied. The strengthening is possible due to the frame's proper operating in accordance with arising seismic loads. The analysis of the loads, which are calculated according to the regulatory documents of Russia and other countries, is presented. As well, the loads have been compared to each other. There is a review of possible experimental methods to determine the frame's strength under the seismic loads in the article. In addition, there are some critics on the existing regulatory documents and on, exactly, the formulas and coefficients used, as well as on the proposed alternative solutions. We have made the research of the effect that soil has on the steel frame's strength characteristics under the seismic loads. Promising constructive solutions for steel frames in case of earthquakes are indicated. The experience of designing the earthquake-resistant structures in other countries has been studied. The materials and documents about the past accidents in Russia and world's other countries have been analyzed. The studying of the influence of the steel frames own vibrations and their constructional forms on the foundation's pliability is also presented here.

1. Introduction
The intensive industrial construction, which is close to the sources of mining, determines the necessity of providing the industrial facilities protection from unforeseen damage due to the seismic effects. Therefore, in the high seismic activity areas, we should give preference to the construction of the industrial buildings with bearing and enclosing steel elements, take measures to improve the constructional forms and seismic protection methods and to increase technical and economic indicators. That's because the steel constructions have the increased seismic resistance compared to the prefabricated and monolithic reinforced concrete constructions, not to mention the structures made of bricks and local materials.

The design of earthquake-resistant steel frames for industrial buildings is based on three fundamental principles:
- The decrease in own weight of the building;
- The reduction of accelerations during the vibrations of the frame constructive elements and the building as a whole;
- The exclusion of large values of forces and stresses when calculating the structure sections.
2. Materials and Methods
Despite the high-degree seismic resistance of steel frames of the industrial buildings, there are numerous examples of their damages and even destruction due to seismic effects.

The analysis of the materials about the past accidents in Russia and in other countries of the world allowed us to identify the following main causes of these damages:
- The violations in the installation work technology – 34%;
- The errors in the executing of the construction linking nodes – 26%;
- The violation of the technical operating rules – 16%;
- The seismic impact level is higher than predicted because of the insufficient justification of the construction site seismicity – 12%;
- The insufficient quality and the dissonance between the designed seismic protection measures and modern requirements – 5%;
- The lack (at present time) of clear recommendations for the industrial building frames seismic protection under high-seismic conditions – 7%.

Thus, even at the design stage, in 24% of cases, the industrial building steel frame is doomed to be subjected to significant damages (up to its destruction) due to the seismic effect. The damages from dynamic effects appear in the form of breaks and elements stability losses, in the growth of the residual deformations, in the form of fatigue cracks in the base metal and welds, and also in the form of the bolt and rivet joints breakdowns.

According to the international experience, in the case of earthquakes the parts of the constructions that are often damaged and destroyed are vertical ties along columns and horizontal ties along the lower and upper zones of trusses. There are also damages and destructions of the stepped columns in the linking nodes of the crane beams with columns (in the form of brittle fracture). As well, the displacements of the columns over the vertical axis are often take place because of the stretching and breaking of the anchor bolts and the destruction of vertical ties between the columns. [13]

In addition to the negative experience of the earthquakes that took place on Earth, there are other essential sources of information about the dynamic processes effecting on the nature and magnitude of the building structures damages, in general, and the industrial building frames damages, in particular. These sources are the experimental studies using models that are similar to real structures. In some cases, these studies serve for verifying the reliability of the proposed theoretical hypothesis and calculation method. In others cases, they allow to determine the actual dynamic characteristics of structures, to analyze the influence of various defects and element damages, and to obtain reliable information about the forms, frequencies and decrements of own vibrations, about the linear and angular displacements, etc.

However, there are only few of such experiments because of their execution complexity and high cost. Most importantly, they won't allow to predict the actual behavior of the constructions in the real seismic conditions. On one hand, it's impossible to create a vibration model due to the multi-wave nature of an earthquake. On the other hand, at the same time it's impossible to take into account the real conditions of interaction between the construction and the base. The base pliability effects on the frequencies and forms of own vibrations of the constructions, thus leading to a significant distortion of the calculated diagrams reflecting the internal force factors of the construction.

By using the dynamic foundation model proposed by D.D. Barkan and O.A. Savinov, we compared all of the seismic calculation numerical results on all of the schemes of one-storied industrial buildings frames proposed for the construction in seismic areas with and without considering the base pliability. This showed us the existence of the construction strength reserve due to the inertia of the elastic base. Moreover, for all of the considered schemes of one-storied industrial buildings frames the ranges of values of own vibrations periods for the fundamental tone were established. The essential thing for the estimation of the construction's stress-strain state appeared to be the consideration of the elastic base pliability. [10]

It should be noted that in the presence of loose soils for rigid structures, where the lateral displacements from the base pliability are comparable with the displacements from the deformations
of the construction itself, considering the soil inertial properties allows to design the construction with the reduction of the seismic impact magnitude up to 2-3 times. So, the SP 14.13330.2014 "Building in the seismic areas" approved in the current standards of Russia needs to be adjusted because of the differentiation of the dynamic coefficient β spectral curve and because of the seismic load increasing by 2 times for loose soils (III category) compared to ordinary soils (II category). The increasing of the construction site seismicity should be taken into account. The numerical studies are to be executed to make corrections to the SP 14.13330.2014. These studies should have calculating nature and must include the certain dynamic parameters of the constructions. Let’s note that in the case of mountainous regions, where the soil is rock solid or large-block and low-moisture (consisting of igneous rocks), which are the soils of I category (in terms of seismic properties), the SP 14.13330.2014 requires to reduce the construction site seismicity by 1 point compared with the seismicity of the area, i.e. to reduce seismic load by 2 times.

In our opinion, such a recommendation, in regard to steel frames, is premature because, on one hand, the inertia effect of the base will be slight, on the other hand, the spectral dynamic coefficient for a steel construction can’t be unified with the standard coefficient βi, that is correct for reinforced concrete structures, due to different values of the damping logarithmic decrement δ. So, if δ = 0.1 for a steel structure, then δ ≈ 0.3 for a reinforced concrete structure, as it was assumed by prof. I.L. Korchinsky, the creator of the modern dynamic theory of seismic resistance.

Based on the solution of the oscillator’s differential equation, we obtained the formula of the dynamic coefficient β at resonance:

\[
\beta = \frac{\pi}{\delta + \frac{\delta_0}{\delta + \delta_0}}
\]

\(\delta_0\) (delta) – damping logarithmic decrement of the base, taken on average equal to 0.1.

This shows that for metal structures \(\beta = 9-10\), while for reinforced concrete structures \(\beta \approx 6\), which was taken as the initial value for the dynamic coefficients \(\beta\), spectral curves.

Therefore, the dynamic coefficient of the seismic effects for one-storied industrial buildings steel frames should be taken higher than for reinforced concrete ones.

There is also a need to clarify the coefficient \(K_i\), which takes into account the acceptable damages for buildings and constructions according to the degree of responsibility.

In accordance with the SP 14.13330.2014, this coefficient for steel frames without vertical ties between the columns is \(K_i = 0.25\), but with the vertical ties it is \(K_i = 0.22\). I.e. the seismic load is reduced by 4-4.5 times and the residual deformations and damages are allowed while providing the safety of people and equipment. At the same time, it’s difficult to say how true all of this is.

Therefore, the existing technique for calculations of the steel frames deformation after the seismic impact seems to be very controversial and imperfect, despite its 100-year development period.

If you analyze the various calculation standards for the seismic loads, you will see that they depend on the regional features / standards, i.e. every leading country in the world has its own calculation method, which is quite different from the others.

After comparing the SP 14.13330.2014 with the standards in the USA, Japan and India, we became sure that the calculation results could greatly vary in quantitative terms. For example, the calculating of one of the constructive schemes of a two-storied industrial building influenced by a 9-point seismic effect, gives differences in maximum values of the bending moments. The differences are up to 4 times. By the way, Russian standards give the lowest results, while Indian ones give the highest. [1,10]

Thus, at present time we have no universal and reliable regulatory framework. First of all the calculations on the constructions influenced by the seismic effects should be provided with the constructive examples that have found a sufficiently clear justification and verification.

3. Results and discussions

We will try to formulate the basic requirements for the steel frames design in the seismic areas:
- The layout of an industrial building should be made in the rectangular form in plan, with symmetrically spaced spans without a difference in elevation for the adjacent spans;
- The anti-seismic seams should be carried out on the paired columns and on one common foundation;
- The mass reduction the coating (as a whole) should be achieved for ensuring its spatial work;
- It's recommended to increase the spatial rigidity of the frame and the stability of the coating (as a whole) by making the intermediate bonds;
- All constructional joints should ensure a smooth flow of efforts without the trajectory sudden changes and the stress concentration zones;
- It's necessary to perform welds by electrodes to ensure ductility of the seams;
- As a rule, there should be a rigid connection of the girth rail with the columns in nodes;
- If there are some rigid frame nodes in the column heads, it's appropriate to replace the bases pinched in the foundations with the hinged fasteners (for columns) and to install the horizontal elastic clamps;
- The vertical connections between the columns should be excluded because these are the elements most susceptible to the seismic effects, especially with high seismicity. It's recommended to accept the frame option not only in the transverse, but also in the longitudinal direction;
- It's necessary to provide the reliable construction fastening in the nodes and in the support places with the installation of shock-absorbing gaskets;
- When using hinged wall panels at the level of support on the column supporting tables, provide horizontal anti-seismic seams filled with elastic gaskets;
- The construction's foundation should be made in the form of a monolithic reinforced concrete slab mounted on flexible piles or sliding on the base;
- While erecting buildings and constructions in the seismic regions, it is appropriate to use special structured piles. They include root-like piles with high bearing capacity that is 4-5 times higher than the bearing capacity of the standard model under static loads and 2 times higher under dynamic ones;
- Along with the passive methods for industrial buildings steel frames, several active special methods for the seismic protection should be provided. They include:
  • The foundation constructions with hanging supports that are used in Japan and Mexico;
  • The structures with roller supports used in Russia, Chile and a number of other countries;
  • The constructions with one-way turning on and off links;
  • A number of others – with the dampers between the foundation and the supporting part of the building in the form of a sliding belt in the foundation with increased dissipative properties; the seismic-isolating rubber-steel cylindrical supports that reduce the seismic effect on the building frame up to 7 times; etc.

4. Conclusions
Using of the pre-stressed sheet wall fencing should be considered promising because this is the system of the increased dissipation with nonlinear damping and intermittently disconnected bonds.

All of the constructive measures for the seismic protection of the steel frames of one-storied industrial buildings systematized in this work can be used in the real conditions for the design.

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