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VIBRATION ANALYSIS OF MODULAR STEEL STRUCTURES SUPPORTING VIBRATORY SCREENS IN A MINERAL PROCESSING PLANT[1]

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Abstract

In industrial plants, modular metallic construction provides many benefits including reduction in construction time and quality fabrication performed in a module assembly yard. Individual modules are generally fabricated and assembled off-site, and transported to the plant site by self propelled modular transporter or other devices, where they are erected in place using various lifting and transportation techniques. The modular structure should be designed so that it is sufficiently robust to withstand all transportation related loads and stresses as well as high vibration levels imposed by vibrating equipments such as vibratory screens and at the same time, not too heavy in order to be transported in a feasible way. This paper presents details of vibrating operational loads on a modular mineral processing plant and the analysis to obtain dynamic response of the structure. The first part of the paper presents the operating principle of vibratory screens and the second part shows the recommended steps in carrying out a vibration analysis to ensure satisfactory dynamic performance of the modular structural steel building supporting vibrating screens. The structural static and dynamic analysis is performed using the finite element analysis software STAAD Pro v8 and the input data for analysis are the equipment static and dynamic forces, provided by the equipment vendor, at the support points of the equipment. The design is checked for acceptability of the vibration displacement amplitudes against allowable vibration levels for human comfort as per international codes.
Key words: Vibration; Metallic structures; Vibratory screen; Modular constructions.

ANÁLISE DE VIBRAÇÃO DE ESTRUTURAS DE AÇO MODULARES SUPORTANDO PENEIRAS VIBRATÓRIAS EM UMA PLANTA DE PROCESSAMENTO MINERAL

Resumo

Em plantas industriais, construção metálica modular fornece muitos benefícios tais como redução no tempo da construção e aumento da qualidade de fabricação, pois os módulos são fabricados em locais apropriados, geralmente distantes do local da planta. Somente depois de fabricados, os módulos são transportados para o local definitivo da planta industrial onde esta é erguida por meio das interconexões destas unidades modulares. Os módulos estruturais devem ser projetados de tal forma que sejam robustos o suficiente para suportar cargas e tensões desenvolvidas durante o transporte, assim como suportar os altos níveis de vibração impostos por equipamentos durante a operação da planta. Por outro lado, não devem ser tão pesados para serem transportados de forma adequada. Este artigo apresenta uma aplicação de análise dinâmica de estruturas de prédio metálico modular contendo cargas impostas por peneiras vibratórias. A primeira parte do trabalho apresenta princípios de operação de peneiras vibratórias e a segunda parte apresenta as etapas da análise dinâmica realizada em um prédio metálico contendo peneiras vibratórias. A análise estática e dinâmica é realizada usando o software de elementos finitos STAAD Pro v8 e os dados de entrada para análise são as cargas estáticas e dinâmicas fornecidas pelo fabricante das peneiras. O projeto dinâmico é avaliado, por meio de normas internacionais, para garantir a integridade estrutural das estruturas metálicas assim como garantir o conforto humano em relação à exposição às vibrações.
Palavras-chave: Vibração; Estruturas metálicas, Peneira vibratória; Construção modular.

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1 INTRODUCTION

Vibratory screens are often one of the main sources of vibration and noise in metallic buildings of mineral processing plants. As those equipments are manufactured to vibrate, the design of its metallic structural supports has crucial importance in order to prevent faults to the system and inconvenience to operators.

The modular construction technique or simply modularization is a construction approach that provides numerous benefits for both constructor and owner, like shorter project duration, reduced number of workers onsite, reduced project costs, improved safety, quality and productivity. This technique has already been used for some time, but in Brazil it is still not very well known.

The design of the modules has to be such that they are sufficiently robust to prevent higher vibration levels, yet not too heavy, in order to be transported in a feasible way. Traditionally, designing massive systems is the solution to avoid vibration concerns, but with modular construction, mass limitations may be required to enable transportation plans. Hence, detailed vibration analysis needs to be carried out to obtain the real dynamic response of the modular structure to the vibratory loads.

This paper presents the design methodology for carrying out vibration analysis of the support structure for vibrating screens, in a modular structural steel building, which forms a part of a modularized mining plant. Initially, the paper discusses the concepts of modular construction and the fundamentals of vibratory screens. Then, the issues about design of metallic structures supporting vibratory screens are addressed. Finally, a case study is presented, where a design is performed by finite element method (FEM) using the commercial software STAAD Pro v8i.

2 MODULAR CONSTRUCTION (MODULARIZATION)

Modularization or modular construction is the construction process of industrial plants (i.e., refineries, oil and mineral processing plants) based in modules assembly. The modules (Figure 1a) contain structural steel frames equipments, piping, electrical instrumentation systems, fire protection, ladders, and other components. These modules are fabricated offsite in specialized fabrication yards (Figure 1b) and then transported to the plant site by self propelled modular transporter (SPMT) or other devices. On site the modules are inter-connected using various lifting and transportation techniques. The benefits of this construction methodology are shorter project duration, reduced number of workers onsite, reduced project costs, improved safety, quality workmanship and increased productivity. More details about modularization can be found in a companion paper.[1]

Figure 1. (a) Module being transported by SPMT; (b) Modules fabrication yard. [2]

3 VIBRATORY SCREENS

In order to obtain iron ore from the ROM (run of mine), the ROM must pass through the crushing and screening operations to achieve the proper commercial granulation. The operation of crushing comprises a set of techniques that aim to reduce a solid to a certain size, in fragments of smaller size by mechanical action. This operation may include several stages: primary, secondary, tertiary and quaternary. Screening is the operation of separating the particles into two or more fractions of different sizes, according to the passage of the particles in the screening surface.

The crushing and screening operations may assume different configurations depending on various parameters. The principal design parameters that drive crushing plant selection and configuration include [3]: production requirements, ore characteristics, project location, operational considerations, climatic conditions, capital cost, safety and environment, life of mine/expansion plans and maintenance requirements. Figure 2 shows a simple flow sheet of two stage open/closed circuit of crushing and screening process.

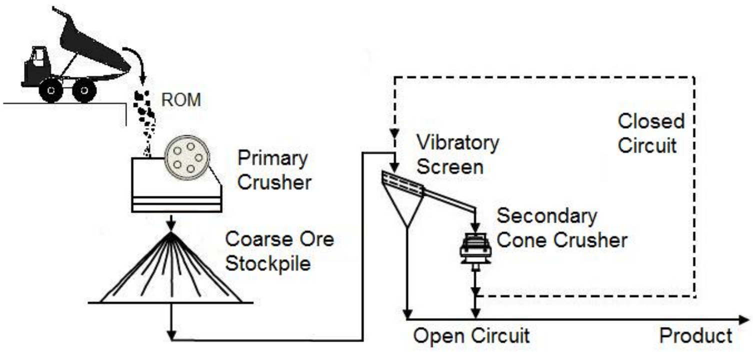

Figure 2. Two stage open/closed circuit.[3]

Vibratory screens (Figure 3) are generally composed of a robust chassis (with several structural reinforcements) called the vibratory screen box, an excitation mechanism which moves the screen and provides forced vibration and one or more decks which are the supports for the screening surfaces. These vibrating screens are generally supported on some kind of vibration isolators (springs or rosta isolators).

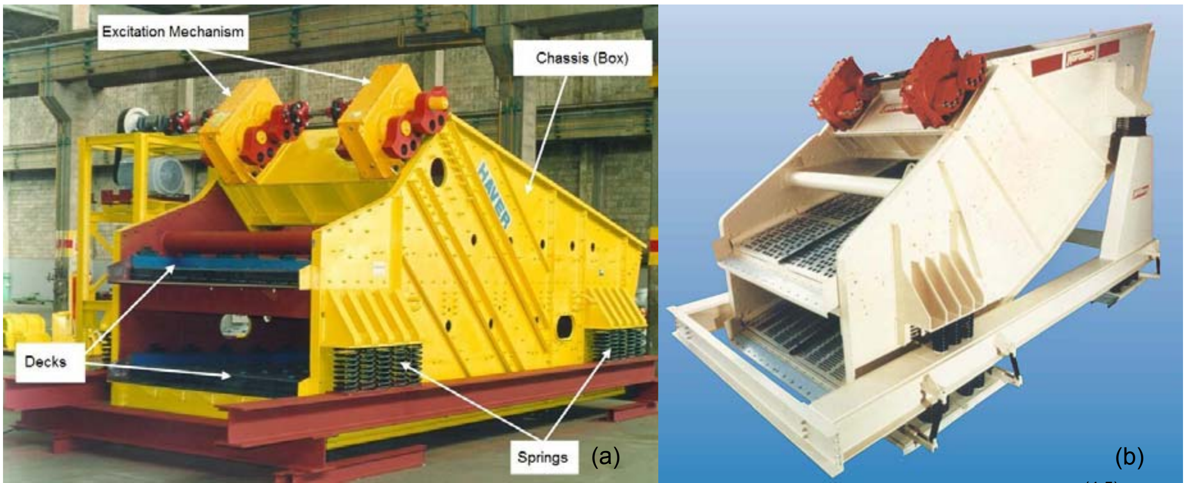

Figure 3. Examples of vibratory screens: (a) horizontal screen and (b) banana screen.[4,5]

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3.1 Movement of Vibratory Screens

There are several types of vibratory screeners used in the industries. The most common are: inclined screens with circular or elliptical movement, horizontal screens with linear or elliptical movement and banana screens.
The inclined vibratory screens (Figure 4a) can have circular or elliptical movement depending on the position of the shaft of the excitation mechanism in relation to the center of gravity of the system. When the shaft is located precisely at the screen's centre of gravity, the entire screen body vibrates with a circular vibration pattern (Figure 4b). When the shaft is installed above or below the centre of gravity (Figure 4c), this placement results in an elliptical motion, slanting forward at the feed end; a circular motion at the centre; and an elliptical motion, slanting backwards at the discharge end.(6)

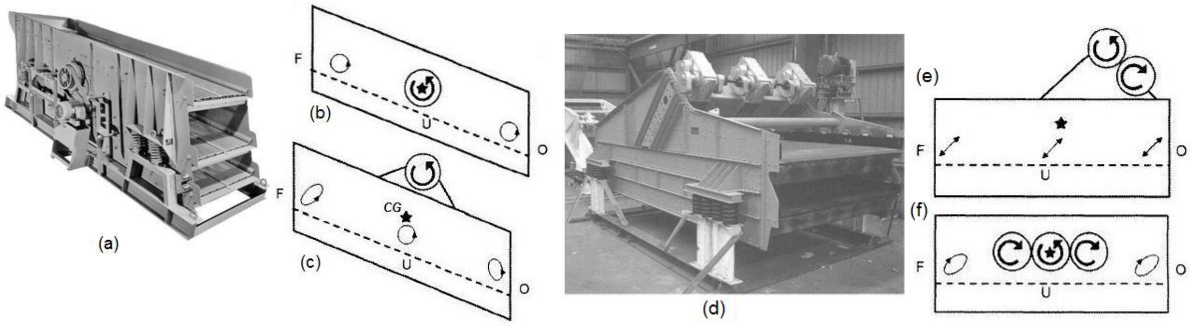

Figure 4. (a) Inclined screen with: (b) circular movement and (c) elliptical movement. (d) Horizontal screen with: (e) rectilinear movement and (f) elliptical movement.(6)

The horizontal vibratory screens (Figure 4d) can have linear or circular movement. This motion can be induced by using mechanical exciters containing matched unbalanced weights rotating in opposite directions on two shafts (Figure 4e). For elliptical vibration in horizontal screens, a three-shaft exciter design can be used to generate this kind of vibratory motion (Figure 4f).(6)
Banana screens (Figure 3b) have multiple inclinations. They have been widely used in sizing applications where both efficiency and capacity are important. These screens typically have a variable slope of around 40° to 30° at the feed end of the screen, reducing to around 0° to 15° with increments from 3.5° to 5º. Banana screens are usually designed with vibration exciters for linear motion.(6)

3.2 Excitation Forces in Screens

There are several mechanisms to apply excitation force to a screen in order to generate the vibratory movements described in the previous section. For circular or elliptical movement, the mechanisms of excitation can be an unbalanced mass connected to a screen shaft. Screens that make use of this kind of mechanism are called two bearing screens(7) (Figure 5).

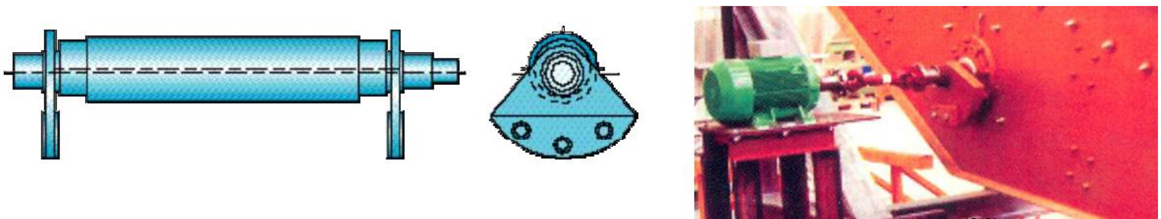

Figure 5. Details of shaft and counterweight of a two bearing screen.(8,9)

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The unbalaced part of the excitation system can be the shaft. In this case, we don’t use counterweights to generate the unbalance force. Actually, the counterweights may be used only to reduce the excitation force caused by the eccentric shaft. In Figure 6a two diferent types of unbalanced shafts are shown. For circular movement, only one shaft (or in odd numbers) must be used.

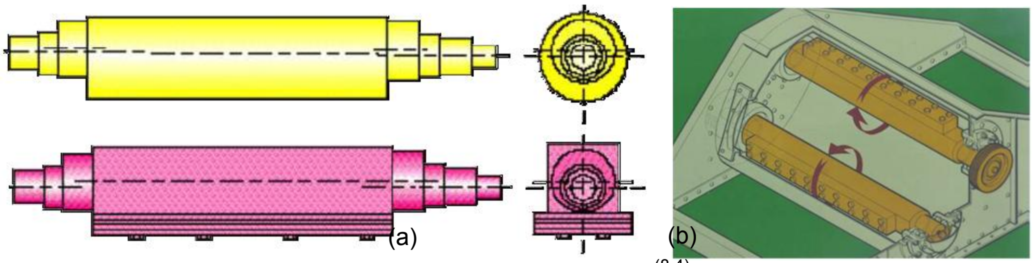

Figure 6. Eccentric shafts.(8,4)

In Figure 6b the two eccentric shafts can be used simultaneously in order to generate a rectilinear movement. In this case the rotational movement of the shafts are in opposite directions. Another way to generate rectlinear movements is the use of unbalanced motors and exciters. In Figure 7 an unbalanced motor is shown. It contains an unbalanced mass at each shaft end. In order to achieve unidirectional force, two motors rotating in opposite directions must be placed in the screen.

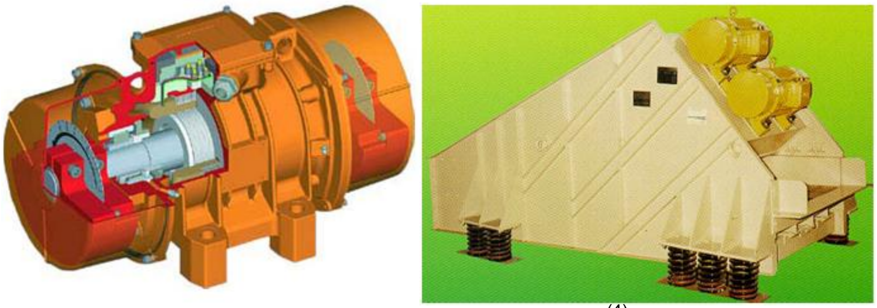

Figure 7. Unbalanced motors.(4)

The other device that produces unidirectional force is the exciter. The operational principle of the exciter is similar to use of two unbalanced motors. The exciter has two shafts and an unbalanced mass in each shaft end. The synchronization of the rotation of the shafts is achieved by means of gears.

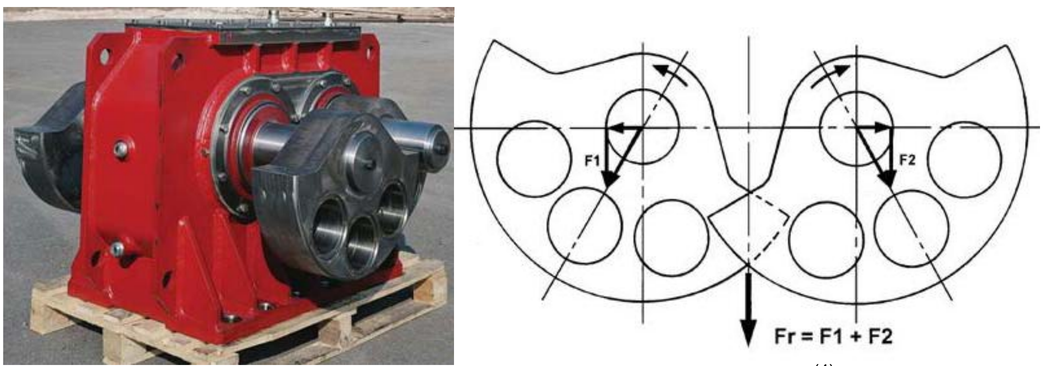

Figure 8. Exciter for generated unidirectional force.(4)

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3.3 Vibration Isolation of Screens

The excitation mechanisms seen in last section generate the vibration of the screen and this vibration is transmitted to its support structures. Thus, vibration isolators must be used between the screen box and the support structures in order to transmit very low force and generate lower vibration levels. The most commonly used isolators are the suspension type consisting of helical steel springs, as we can see in Figures 3, 7 and 9a, while the other type of isolators is the Rosta oscillating mounting (Figure 9b).

Figure 9. (a) Two stage helical spring isolator; (b) Rosta isolators.[10,11]

In order to achieve more isolation of the transmitted force from the excitation mechanism to support structures, an isolator frame can sometimes be used. Basically, the isolator frame is a spring-mass system connected in series with the screen-suspension system forming a two stage isolator. The additional vibration isolation frame added to the existing system will add more mass on the module which is not desirable for transportation, but the reduction of the transmitted vibrating forces on the supporting modular structure outweighs the disadvantage of the mass increase.

4 DESIGN OF STRUCTURES SUPPORTING VIBRATORY SCREENS

Mining plants often use vibrating screens which are an important constituent of the overall plant process. These screens generally vibrate at 3 g to 5 g and produce vibrations which are detrimental to both occupants and other sensitive instrumentation in the plant. The supporting structural framework needs to be efficiently designed to limit the vibrations produced by the vibrating screens. This can only be achieved by taking into account the overall response of the structure which is generally affected by two main components, the vibratory loads produced by the equipment and transmitted to the support structure and the soil properties affecting the soil-structure interaction.

The equipment generated dynamic forces can be calculated or measured, or both. In order to calculate the transmitted force, a model has to be constructed. Screen vibration models can range from a few degrees of freedom to hundreds of degrees of freedom in a finite element model (FEM) (Figure 10a). To obtain the forces transmitted by the machine to the support structure, we first need to know the excitation forces, applied to the screen (Figure 10b). By inputting the excitation forces in the finite element model, we can obtain the reactions at the support points of the machine which in fact are the forces transmitted by the vibrating screen to the

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support structure. Furthermore, for accurate response, the model has to be validated, usually by experimental data. This procedure is generally carried out by the screen vendor and the applied dynamic forces at the machine support points, in vertical and horizontal directions (Figure 10b) are passed on to the client for initiating further analysis of the support structure.

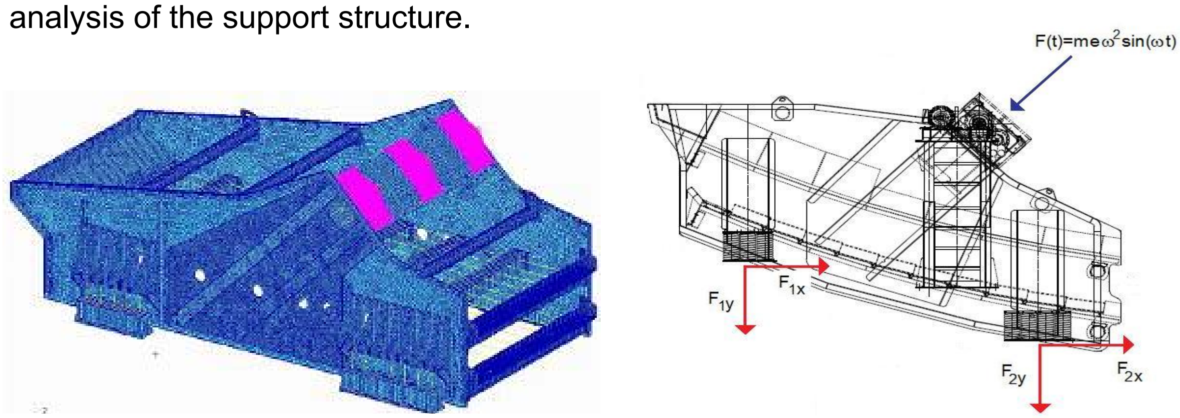

Figure 10. (a) FEM model a vibratory screen; (b) Applied and transmitted forces.[4]

5 CASE STUDY

This section of the paper presents details of the vibration analysis performed on a modular structural steel building supporting vibrating screens. Since modular structures are constructed in the module yard and then transported to the plant site for final assembly, the traditional approach to dynamic loads of adding extra mass can be an extra burden for transportation devices. In these circumstances it is essential to obtain the real response of the structure by carrying out a time history analysis that will describe the variation of loads in time.
The building structure is composed of eight structural steel modules which are supported on a pile foundation. Each individual module is transported completely equipped with all functional machinery and equipment (like silos, screens etc.) and is field connected on site. The modularization process ensures quality fabrication and accelerated construction.
Figures 11a and 11b show 3D model pictures of the assembled building structure and the placement of the six adjacent vibrating banana screens inside the building. The complete structure with the equipment was analyzed for vibratory loads and the results assessed for acceptability based on commonly used vibration acceptance criteria.

5.1 Foundation parameters

To simplify the analysis, it has been a common practice among structural engineers to ignore the foundation flexibility and model the columns with fixed support conditions (no translation, no rotation) at the foundation level. This is not an accurate assumption because the soil conditions and the foundation type will dynamically interact with the structure. To include this interaction effect in the dynamic response of the structure, the software DYNA6 was used to calculate the stiffness and damping of the pile foundation, using the layered option which considers properties of the soil layers around the piles. These foundation parameters as obtained by DYNA6 were fed to the structural model incorporating linear springs, and this model was used to obtain the overall dynamic response of the structure.

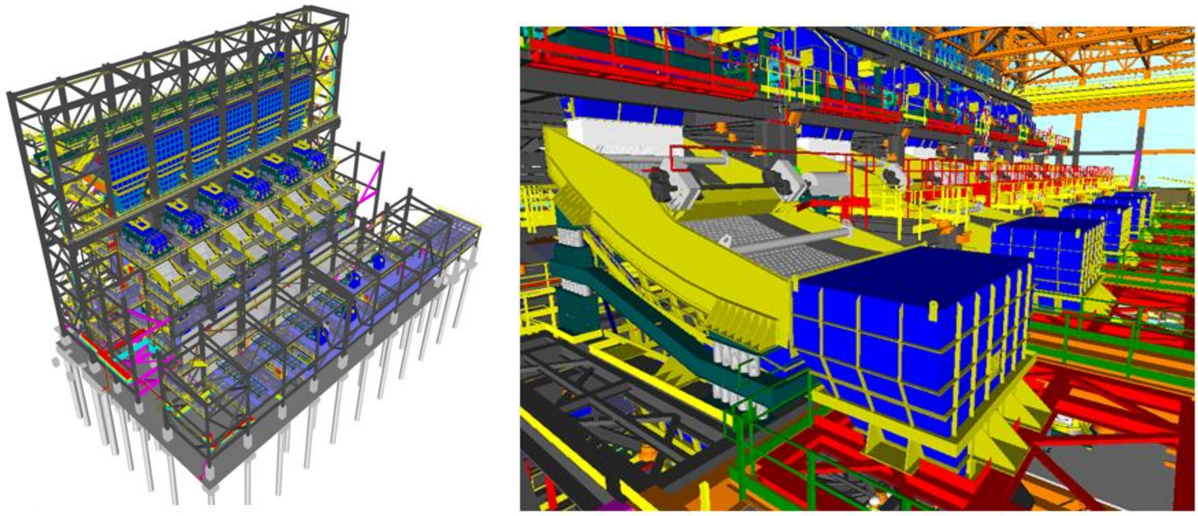

Figure 11. (a) Modular building structure; (b) Banana screens inside the building.

5.2 Equipment information

The dynamic loads applied by the vibrating screens at support locations, were obtained from the vendor prints provided by the equipment manufacturers. These loads were separately presented for operational as well as start/stop conditions. The operational dynamic loads are of interest for serviceability limit states whereas the start/stop dynamic loads are used for structural integrity at ultimate limit states. In addition to the dynamic loads, the critical frequency range of the machine was also provided by the equipment vendor. The nominal operating frequency of the screens was given as 785 rpm.
Figure 12 shows the schematic drawing of the vibrating banana screens and a vendor supplied loading table giving magnitude of the dynamic loads at each support location. To reduce the intensity of the dynamic loads transmitted by the screens to the supporting building frame, the equipment was supplied on a vibration isolation frame, as seen in the figure.

5.3 Dynamic Analysis

The commercial structural analysis and design software STAAD. Pro V8i was used to carry out the dynamic analysis. STAAD is equipped with the facility to perform a response history analysis on structures which are subjected to time varying forcing function loads at the joints. This analysis is performed using the modal superposition method and the screen vibrating loads given in the loading table are applied as harmonic loads of the form:

$F(t) = F_0 \sin(\omega t + \varphi)$,

where, $F(t)$ = Value of the force at any instant of time 't'
F_0 = Peak value of the force
ω = Frequency of the forcing function
φ = Phase Angle

A modal analysis is also performed which provides the desired number of natural frequencies and mode shapes of the structure which are the primary parameters that affect the response of a structure under dynamic loading. Results of the frequency and mode shape calculations may vary, depending upon the mass modeling. Hence,

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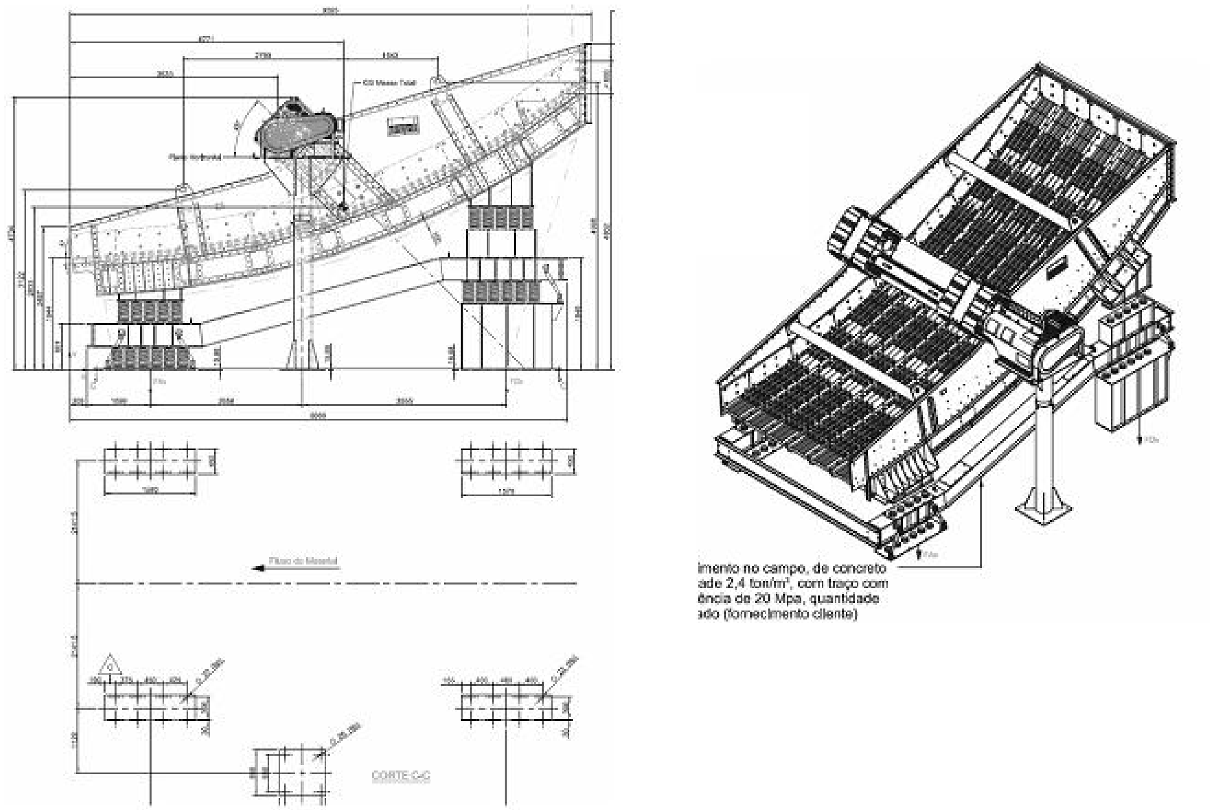
accurate mass modeling is required to correctly assess the behaviour of the real structure. STAAD uses a diagonal mass matrix of six lumped mass equations per joint. The self weight or uniformly loaded member is lumped 50% to each joint.



CARGAS POR CADA APOIO (Com material) – Vide Diagrama de Cargas				
		ALIMENTAÇÃO	DESCARGA	FREQUÊNCIA
VERTICAL	ESTÁTICA:	FAv = 69728 N	FDv= 70709 N	0 rpm
	DINÂMICA EM REGIME (+/-):	FAv = 810 N	FDv = 810 N	785 rpm
	DINÂMICA NA PARADA (+/-):	FAv = 27000 N	FDv = 27000 N	100~300 rpm
HORIZONTAL	DINÂMICA EM REGIME (+/-):	FAh = 486 N	FDh = 486 N	785 rpm
	DINÂMICA NA PARADA (+/-):	FAh = 27000 N	FDh = 27000 N	100~300 rpm
ESTÁTICA NA BASE DE MOTORIZAÇÃO		FM = 15691 N		

Figure 12. Schematic drawing and loading table of banana screen.

5.4 Structural Model

The structural model of the building is shown in Figures 13a and 13b. It uses an assembled structure with all eight modules, acted upon by all six vibrating screens, acting in phase. To capture the best possible behaviour of the structure, it was decided to model the complete structure instead of relying on sub-structuring. The down side of such an action is the requirement of extremely high computational capabilities to deal with the extremely high number of degrees of freedom in the model. This was made possible by activating the advanced solver mode of STAAD. Pro V8i.

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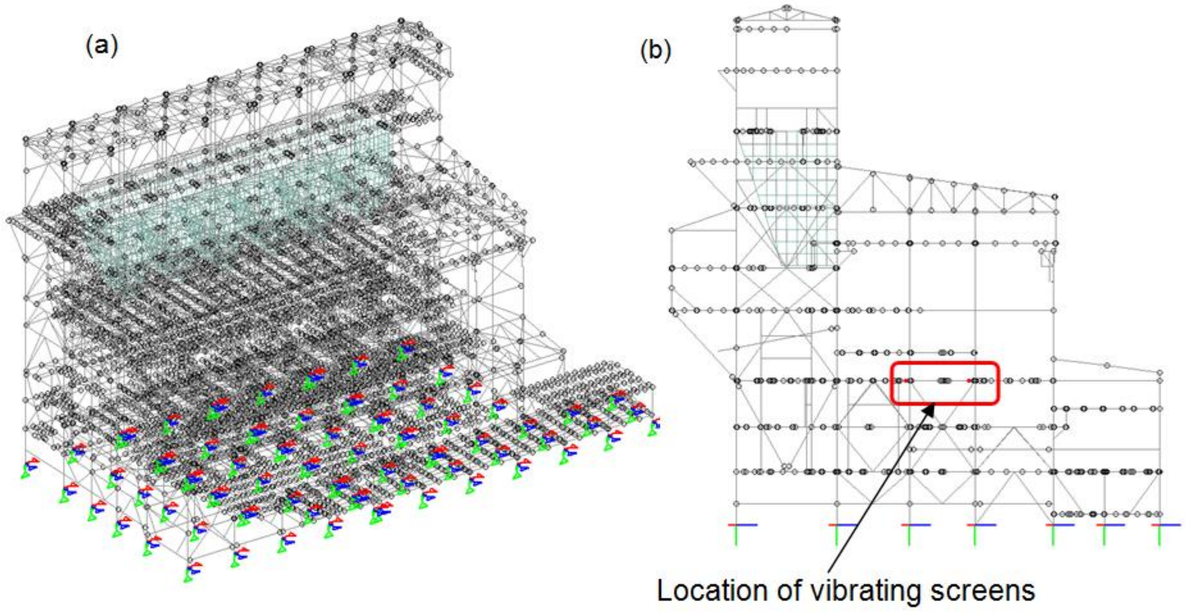

Figure 13. (a) 3D view of the structural model; (b) Side view of the structural model.

5.5 Dynamic Analysis Inputs and Results

The arrangement or the order of the application of dynamic loads from six adjacent screens on the structure is difficult to predict since the screens can actually run in any different number of combinations. In a harmonic forcing function, this parameter can be included as a phase difference or a phase shift. However, because of the very large number of combinations possible with phase shifting among the different screens and phase shifting among even the support locations of the same screen, it was decided to apply all the dynamic loads from all the screens in phase. Although this approach is conservative, it is however feasible and time efficient to obtain the first set of results for assessment against the vibration acceptance criteria. Both the vertical and horizontal dynamic loads were applied as Sine functions, however, the horizontal loads were applied with a phase angle of 90 degrees to incorporate the lag between the vertical and horizontal time dependent loads.

The maximum values of zero to peak nodal displacement amplitudes obtained from the time history analysis in STAAD.Pro, anywhere in the building structure are shown in Figure 14. The time-displacement plot for the node showing maximum vibration amplitude in the horizontal direction is shown in Figure 15a. A review of the first 200 modes of the structure revealed that most of the mass participation was confined to the first 30 modes of vibration and the first and third modes were the most dominant modes with frequencies of 1.3 Hz and 1.5 Hz. with some higher modes (#157) at 6.0 Hz. having minor mass participation. Since the banana screens vibrate with a nominal operational frequency of 13 Hz. (785 rpm), therefore the risk of resonance was highly unlikely even considering the higher modes. The vibration displacement amplitudes from the STAAD time history analysis were compared to the common industry standards used for vibration acceptance.

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	Node	L/C	Horizontal X mm	Vertical Y mm	Horizontal Z mm	Resultant mm
Max X	13932	1 DYNAMIC LOAD CASE	**0.003**	0.000	0.001	0.003
Min X	13934	1 DYNAMIC LOAD CASE	**-0.002**	-0.000	0.002	0.003
Max Y	8937	1 DYNAMIC LOAD CASE	0.000	**0.001**	0.004	0.005
Min Y	8955	1 DYNAMIC LOAD CASE	-0.000	**-0.003**	0.002	0.004
Max Z	6945	1 DYNAMIC LOAD CASE	-0.000	0.000	**0.006**	0.006
Min Z	9079	1 DYNAMIC LOAD CASE	-0.000	0.000	**-0.005**	0.005

Figure 14. Summary of maximum displacement amplitudes in the model.

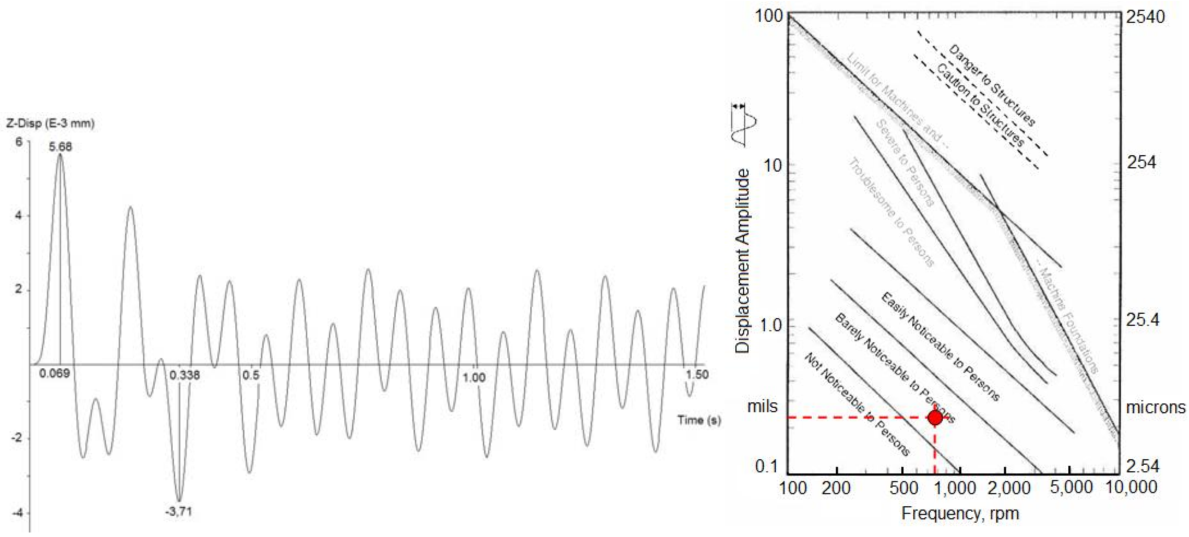

Figure 15. (a)Time-displacement plot for node 6945; (b) Vibration acceptance criteria.

5.6 Vibration Acceptance Criteria

The standards most extensively used for assessing the acceptability of vibrations in structures supporting vibrating machinery are ISO10816, Blake's chart, Baxter & Bernhard, DIN4150, API610 and Reiher-Meister Chart for mining operations. Using the Reiher-Meister Chart,(12) the maximum displacement amplitude from the analysis was plotted and assessed for vibration acceptance. As evident from Figure 15b, this amplitude falls in the "Barely Noticeable" range and is hence acceptable for the successful operation of the machine as well as human occupancy of the plant modular structure.

6 CONCLUDING REMARKS

For most special applications, it is essential to carry out a vibration analysis on structures which are subjected to vibrating machine loads. Since modularization requires transportation, excessive use of massive elements creates hurdles in transportation convenience which can be avoided by incorporating vibration isolators. The use of time history analysis on the numerical model of the whole assembled modular structure is computationally intensive but provides the real dynamic response of the overall structure which can be assessed for acceptability against most available standards.

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