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ABOUT SIMULATION OF VIBRATORY COMPACTION EQUIPMENT WITH COMPOSITE MATERIALS INCORPORATED

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Abstract: *In this paper, the authors addressed the topic of computational simulation of composite materials from the constructive structure of vibratory compaction equipment (roller, rammer, vibratory plate). The aspects that must be considered for the development of dynamic models that accurately simulate the engineering phenomenon have been identified. In the current context of the digitization of industry 4.0, the estimation based on such models of the efficiency of the compaction process is of great relevance.*

Keywords: *compactors, advanced composite materials, challenges, computational simulation*

1. INTRODUCTION

Some compaction quality control techniques to improve the efficiency of construction work are based on monitoring the response parameters of a dynamic model subjected to computer simulation [1,2]. The adoption of the dynamic vibration model for its integration into AI, BIM, data mining or intelligent control must consider the dynamic behavior of each part embedded in the analyzed machine-land system. Changing the materials from which component parts of the compactor structure are made leads to the modification of some parameters that have a significant influence on the efficiency of the vibration compaction process, such as: mass, stiffness, rigidities etc. Vibratory compaction involves a technological process where a vibrating tool applies oscillating forces transmitted into terrain or construction materials. Currently, the incorporation of composite materials in the construction of compaction equipment brings significant benefits, such as weight reduction, increased corrosion resistance, increased service life etc. The manufacture of these materials involves the use of several principles and methods aimed at ensuring optimal fiber alignment, resin distribution and void elimination [3-5].

2. APPLICABILITY OF COMPOSITE MATERIALS IN COMPACTOR EQUIPMENTS FABRICATION

In the last decade, composite materials are increasingly used in the manufacturing of compaction equipment due to their outstanding features, such as high strength-to-weight ratio, durability, and resistance to corrosion and wear. In Table 1 are shown the composite materials commonly used in equipment for vibratory compaction.

Table 1. Examples of the compactor parts fabricated with composite materials

Composite materials	Products	Benefits
Glass Fiber-Reinforced Polymer (GFRP)	• Covers and housings • Handlebars and frames	GFRP offers a good balance of strength, flexibility, and cost-effectiveness. It is lightweight and resistant to corrosion, making it suitable for components that require both strength and durability.
Carbon Fiber-Reinforced Polymer (CFRP)	• Structural components • Vibration damping	CFRP is known for its high strength-to-weight ratio, excellent stiffness, and fatigue resistance. It is more expensive than GFRP but offers superior performance, especially in high-stress applications.
Aramid Fiber-Reinforced Polymer	• Drive Belts • Protective layers	Aramid fibers offer excellent tensile strength, impact resistance, and abrasion resistance, making them ideal for applications that require high durability under dynamic loads.
Metal Matrix Composites (MMCs)	• Feet of the rammer • Drum of the roller	MMCs offer enhanced mechanical properties, such as higher strength, stiffness, and wear resistance compared to the base metal. They also maintain good thermal conductivity and are more resistant to thermal degradation.
Polyurethane Composites	• Bellows and seals • Vibration pads	Polyurethane composites are flexible, durable, and resistant to abrasion and impact. They also have good vibration damping properties.
Rubber-Fiber Composites	• Shock absorbers • Drive belts and pads	These composites offer excellent elasticity, impact resistance, and wear resistance. They are particularly useful for applications requiring significant flexibility and durability.
Ceramic Matrix Composites (CMCs)	High-temperature components	CMCs are known for their excellent thermal stability, high strength at elevated temperatures, and resistance to wear and corrosion
Hybrid Composites	Custom components	Hybrid composites allow for the optimization of specific properties, such as balancing strength, stiffness, and cost.

Currently, the chassis or the main frame of the technological equipment, as well as the working organs (drum or base plate at vibratory plate and rammer) are made of materials based on composites with glass fiber or carbon fiber giving high resistance to abrasion compared to traditional materials (such as steel or its alloys) and reducing the transmission of unwanted vibrations to the user operator [6]. The realization of anti-vibration elements from elastomeric materials (such as fiber-reinforced elastomers) leads to an increase in the level of vibration damping in the structural elements of the equipment (extending the life of the technological compaction equipment), as well as the comfort of the attendant operator. The use of fiberglass or carbon fiber composite materials in the engine housing provides greater corrosion resistance in harsh working environments and helps reduce overall weight. Also, the control lever and handles are easier to handle and more comfortable for the operator, if they are made of fiber-reinforced plastic composite materials, offering an ergonomic design, increased resistance to wear and tough working conditions. The joining parts and supports in the structure of the equipment that ensure the connection and support of the various components of the vibratory compaction equipment are also made of composite materials with carbon fiber or glass, thus offering increased resistance to traction and bending, being ideal for parts that must be at the same time light and durable. Thus, the engine impact protection housing is made of a single piece made of high strength composite material (Figure 1).

Figure 1: New material used to protective housing of the compactors equipment [13-15]

In addition, the drive belts are much more resistant to high tensions and more stable under the action of variable loads after the traditional rubber was replaced with aramid fiber composite (Figure 2).

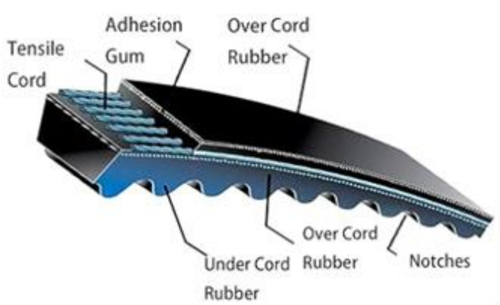

Figure 2: The structure of a belt drive with aramid fiber composite

The main advantages of aramid composite material are high tensile strength, durability, dimensional stability, heat resistance. A comparison between the two materials (rubber and aramid fiber composite) is given in Table 2.

Table 2. Summary of material properties: rubber belt vs aramid fiber composite belt

Properties / Material	Rubber	Aramid fiber composite
Density	1.1 - 1.5 g/cm³	around 1.44 g/cm³
Young’s modulus	2 - 10 MPa	70 - 180 GPa
Poisson’s ratio	0.45 – 0.50	0.35
Tensile strength	10 - 30 MPa	3600 MPa
Heat resistance	100°C	150 - 200°C
Elongation at break	500 %	less than 5%
Flexibility	Highly	Less (more rigid)

Although currently the working tools (e.g. drums or base plates) of vibratory compactors are made of metallic materials, there is a significant potential for the use of composite materials in the future, depending on technological progress and market requirements.

3. CHALLENGES TO SIMULATION OF THE DYNAMIC BEHAVIOR OF COMPACTION EQUIPMENTS

The simulation of the behavior of a transmission with an aramid material belt must highlight the efficient transmission of power (without significant energy losses at high speeds), the dynamic behavior under variable load conditions (without permanent deformations or stretches), the reduction of vibrations and noise in performance, flexibility and fatigue resistance (and implicitly extended life even under continuous or cyclical operating conditions). Dedicated software applications are available to simulate the dynamic behavior of the belt transmission system, such as: ANSYS, Abaqus, LS-DYNA, Matlab etc. The results of data processing that are of interest in this case refer to: stress and strain analysis (stress distributions, strain rates, and identify potential failure points in the composite), dynamic response (vibrational modes, resonance frequencies, and damping characteristics) and fatigue life under cyclic loading conditions.

Regarding the overall approach of a compaction equipment such as a roller, then the aspects targeted by the simulation of the technological process are oriented to the evaluation of the operational performance. In this regard, the linear elastic two-degree-of-freedom model is frequently used for the vibration compaction simulation process, which model is based on the linear elastic vibration theory and uses the mass-spring-damping system to describe roller-terrain vibratory system. As shown in Figure 3 (ks is the elastic stiffness of the terrain; cs is the damping of the soil; kf is the stiffness of the shock absorber; cf is the damping of the shock absorber; xf is the displacement of the upper frame; xd is the displacement of the vibratory drum), the model simplifies the vibratory roller into two main parts, namely, the upper frame and the vibratory drum. Both parts are connected by a damping system, the terrain is supposed to a preponderantly elastic body, and the Kelvin model is used to simulate the behavior of the terrain.

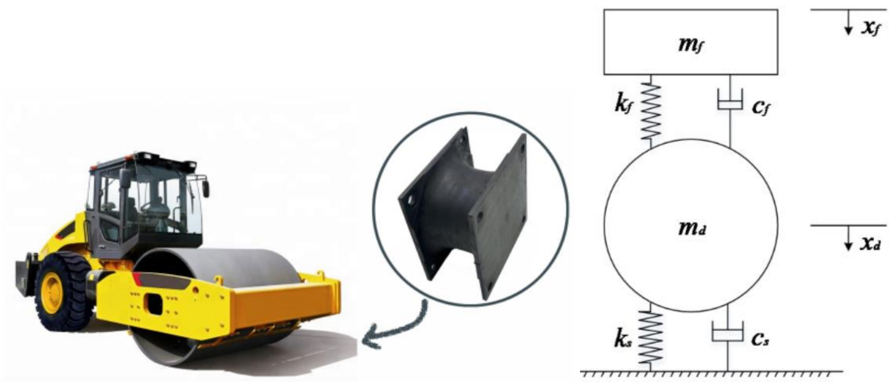

Figure 3: 2-DOF dynamic model for behavior simulation of the vibratory compaction process

The dynamic differential equation of the model is expressed as:

$$\begin{bmatrix} m_f & 0 \\ 0 & m_d \end{bmatrix} \begin{Bmatrix} \ddot{x}_f \\ \ddot{x}_d \end{Bmatrix} + \begin{bmatrix} c_f & -c_f \\ -c_f & c_f + c_d \end{bmatrix} \begin{Bmatrix} \dot{x}_f \\ \dot{x}_d \end{Bmatrix} + \begin{bmatrix} k_f & -k_f \\ -k_f & k_f + k_d \end{bmatrix} \begin{Bmatrix} x_f \\ x_d \end{Bmatrix} + \begin{bmatrix} m_f \\ m_d \end{bmatrix} = \begin{Bmatrix} 0 \\ F_0 sin\omega t \end{Bmatrix}, \quad (1)$$

where m_f is the mass of the upper frame; m_d is the mass of the vibratory drum; $\dot{x_f}$ and $\ddot{x_f}$ are the speed and acceleration of the upper frame, respectively; $\dot{x_d}$ and $\ddot{x_d}$ are the speed and acceleration of the vibratory drum, respectively; F_0 is the dynamic force; ω is the rotational speed of the eccentric mass; t is time.

By changing the traditional material with composite material, a reconsidered approach of the dynamic model of compactor-terrain interaction are needed. This implies detailed knowledge of the inertial characteristics as an effect of reducing the mass of the component elements (m_d and m_f), the stiffness and damping characteristics of the anti-vibration elements (k_f and c_f), the range of values of the natural vibrations of the replaced parts for avoided resonance under working conditions, etc. The basic idea of a vibration compaction model is the accuracy with which it simulates the vibration compaction process, by evaluating the dynamic response of the soil-working tool interaction, the deformation of the filling materials and the influence of different parameters on the compaction effect [7,8] etc. In the specialized literature [9], the study of this interaction was carried out based on many vibration compaction models (linear and nonlinear elastic, viscoelastic, viscoelastic plastic, etc.) with the aim of analyzing the influence of different compaction parameters on the dynamic characteristics and compaction effects of system, to provide a theoretical evaluation. In this way, by adopting an adequate model for simulation, the influence of the structural parameters (the distribution of the quality of the upper and lower parts, the stiffness and rigidity of the damper), the operating parameters (amplitude and frequency of vibration, dynamic force), and the soil parameters (stiffness and rigidity) on the dynamic response of the vibratory roller–terrain system can be analyzed.

At present, for vibrations isolations three types of damping materials that are widely used: damping alloy, viscoelastic damping and composites materials [10-12]. Simulation of vibration absorbers made of advanced composite materials involves consideration of the following aspects in order to obtain accurate and useful results:

a) composite material properties: modulus of elasticity, tensile strength, compressive strength, Poisson's ratio, density, damping, etc. Some composite materials have anisotropic mechanical properties, have different internal damping depending on the matrix used and fiber arrangement, and their density influences the dynamic behavior of the absorber.
b) the layered structure of the composite material: configuration of the layers by fiber orientation, the thickness of each layer, and the layering sequence can significantly influence the dynamic behavior, and the interlaminar interaction must be simulated to evaluate the fatigue resistance.

In working conditions with high-amplitude or high-frequency vibrations, vibration absorbers can have a non-linear behavior of the material which is important in choosing the appropriate damping model (viscoelastic, hysteretic, etc.) to correctly simulate the vibration damping generated by the tool active work of the compactor. The natural frequencies depend on the geometry, support conditions, material properties and layered configuration of the composite. Thus, the knowledge of the natural frequencies and natural modes of vibration of the absorber through a modal analysis (using the Finite Element Method) is necessary to evaluate its performance under resonant conditions.

4. CONCLUSIONS

The use of composite materials by major compactors manufacturers expected to become a very common practice in the fields of construction equipment industry, based on the multiple benefits, as: weight reduction, increased strength and durability, and improved operator efficiency and comfort. Simulating mechanical systems based on composite materials is a complex goal that requires advanced modeling methods, significant computational resources, and a deep understanding of the behavior of these materials under different working conditions. The simulation of composite materials requires the development of complex multi-scale models that highlight the behavior at different scales, from the macro level (general structural behavior) to the micro level (fiber and matrix structure). The computational cost can be extremely high requiring the development of efficient algorithms to reduce the computation time. As composite materials are in continuous development, new combinations of fibers and matrices will be created frequently, making simulation models flexible and able to adapt to new materials. The correlation of simulation results with experimental data is what leads to the validation of the dynamic model, thus ensuring the accuracy of the simulation process of the real phenomenon.

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