APPLYING DYNAMIC AND FATIGUE ANALYSIS ON BULK MATERIALS HANDLING EQUIPMENT, STRUCTURES AND COMPONENTS

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ABSTRACT

Bulk material handling structures and equipment are subject to variable and dynamic loads. But when is the design governed by them? When is fatigue a relevant factor and when is it not? This is a subject normally neglected and poorly understood.

Examples taken from the actual operating life of equipment are discussed where these factors are relevant. Both successes and failures are used as examples. Conveyor belts, pulleys, conveyor support structures, boom stackers and bridge reclaimers are included.

1. INTRODUCTION

The words 'fatigue' and 'dynamics' are often used in the bulk materials handling industry, but are not widely understood. Fatigue refers to the effects of variable forces or stresses in the life of a component, while dynamics refers to the effect of transient forces, both instantaneously and over time as a result of fatigue.

Whether considering conveyor belting, idlers and pulleys, their supporting structures, or mobile material handling machines such as stackers and reclaimers, transient dynamic forces are present. These forces are normally generated by starting and stopping or external phenomena such as earthquakes or collisions.

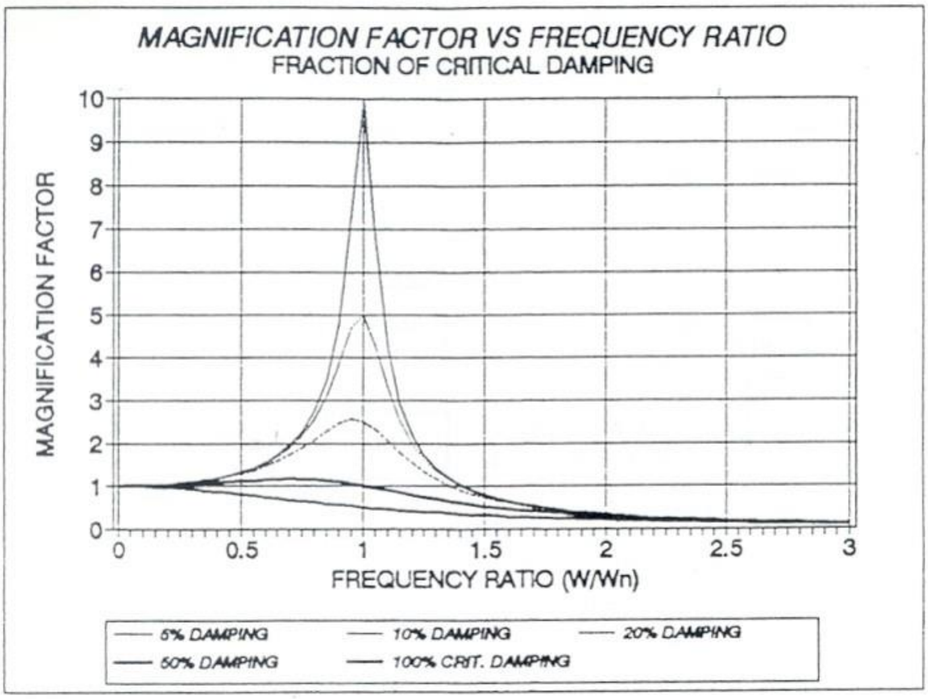
Fatigue is produced by stress fluctuations over time, sometimes related to repeated transient forces, other times to cyclical stress variations. Many times, the failure of an old structure or component is attributed to fatigue, while collapse is produced by corrosion, wear and tear or a one-off event such a storm or a large impact ,or operating the equipment outside its design parameters.2. Belt Conveyors

2.1 CONVEYOR DYNAMICS

Transient forces generated during starting and stopping of conveyor belts are well documented[1] and their calculation is incorporated in commercial software available in the market. However, it is still far from being as widely understood as water hammer phenomena in hydraulics or transient behaviour in electrical grids, even though the mathematical principles are quite similar. Also similar are the dangers of catastrophic failure in large or complex systems.

In a nutshell, the cause of dynamic problems in belt conveyors is the application of forces in a period similar or smaller than the system's natural period, as it causes a dynamic magnification effect as shown in Figure 1. This could be the start-up of a long belt or the stopping of a high incline system. A simple rule of thumb from Dr Funke, one of the pioneers in the field who started his work in the 60s, is to count one second per kilometre of length as an estimate of the half-period of the system and apply any change in force or speed in periods five times greater. In his work[2], he called it 'stress wave traveling time', as he was an electrical engineer and used grid dynamics nomenclature. This corresponds roughly with the behaviour of a steel cord system, while fabric belts have much longer natural periods and are therefore more prone to dynamic problems, even in relatively short conveyors.

Figure 1. Dynamic magnification factor.



Non-transient problems are normally related to resonance of the supporting structures due to the operation of the belt. The most frequent culprit is the rotation of the idlers. Rolls with high eccentricity or presenting material build-up will produce a dynamic force in the rotation frequency of the rolls. If the natural frequency of the belt in the transversal direction is close to the exciting frequency, significant vibrations might appear, sometimes strong enough to cause bearing or structural fatigue failure, but in any case, quite detrimental to the roll life.

Transient and non-transient dynamic effects can be calculated using published formulae[1] or even commercial belt conveyor calculation software. As a basic principle, a large capacity, long and/or fast conveyor should be subject to a preliminary evaluation regarding dynamic analysis to avoid potential problems.

2.2 BELT SPLICES

Belt rating is traditionally selected based on a static safety factor above the maximum operating tension. Usually 10 for fabric belts and 6.7 for steel cord belts. Experience shows that when a belt fails it does so in the splice, and research over the last 30 years or so has shown that apart from edge tension, mechanical damage or workmanship problems, most splice failures are caused by fatigue.

In actual fact, steel cords and fabric plies are not themselves subject to fatigue, but rather the rubber that holds them together. Figure 2 shows a typical steel cord splice layout. Cords are cut and laid next to each other in a staggered pattern. Bonding rubber is placed in the gap between the cords, rubber sheets are placed to complete the covers and the joint vulcanised. After this, forces are transmitted from one side of the splice to the other by the bonding rubber acting in shear. Something similar happens between the layers of a fabric belt splice.

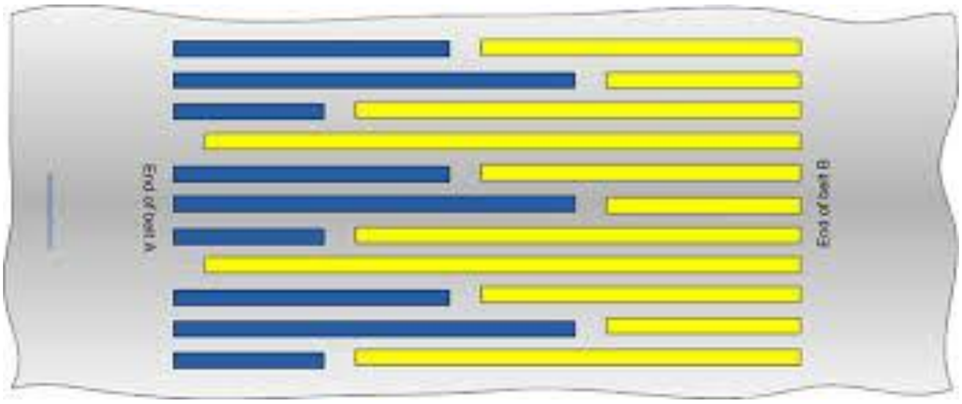


Figure 2. Steel cord splice diagram.

As far back as 15 years, DIN revised their well-known 22101 standard[3] to include transient forces and splice fatigue in the election of belt rating. However, the change has had little impact in the way belts are designed to date. For large installations, taking into account that dynamic and fatigue behaviour can lead to lower capital and operational costs and at the same time increase the reliability of the system. High tension belts present lower splice fatigue resistance due to the limited space between cords to transmit the forces as the cords are bigger. Pulley selection and layout also has a large influence in splice fatigue life. The bottom line is that a lower rating belt, with the right pulley layout and splice design might be more reliable than a stronger belt. Splice strength is not always directly proportional to fatigue resistance[4].

2.3 CONVEYOR STRINGERS

With the use of faster and longer conveyors, the need to optimise the stringer design has become more and more important. High speeds and capacities lead to a point where the dominating factor in the selection of a stringer section is the dynamic response and not the static design criteria.

Figure 3. Overland conveyor structure.

Static calculation is based on allowable stress and deformation while dynamic calculation requires the avoidance of resonance between the rotating idlers and the stringer. As a rule of thumb, the natural frequency required for the structure is at least double the rotating frequency of the idlers.

The saving obtained by using smaller diameter idlers could be lost by the need for a heavier structure in a fast conveyor.

Failure to identify the relationship between transversal belt vibrations, idler rotations and supporting structures is a common mistake made by unqualified designers that lead to problems in the field.

2.4. CONVEYOR PULLEYS

Conveyor pulleys, subjected to thousands of load cycles per hour, usually fail due to fatigue. Even so, the design requirements of fatigue design are not widely understood beyond the shaft design, and that is well documented[5]. Old Excel spreadsheets are still used for pulley calculation, using some formulas derived before the advent of finite element analysis. Examples of these spreadsheets can be found in engineering offices all over the world. These programs derive results regarding end disc and shell thickness that seem to have little relation to actual requirements and are not related to the real problem in pulley construction: welds!

It is not only the position of a weld that is relevant, also the type of weld, as described in many design standards[6]. Figure 4 shows the effect of the type of weld on endurance resistance for the same material. A full penetration weld can have several times the resistance of a fillet weld.

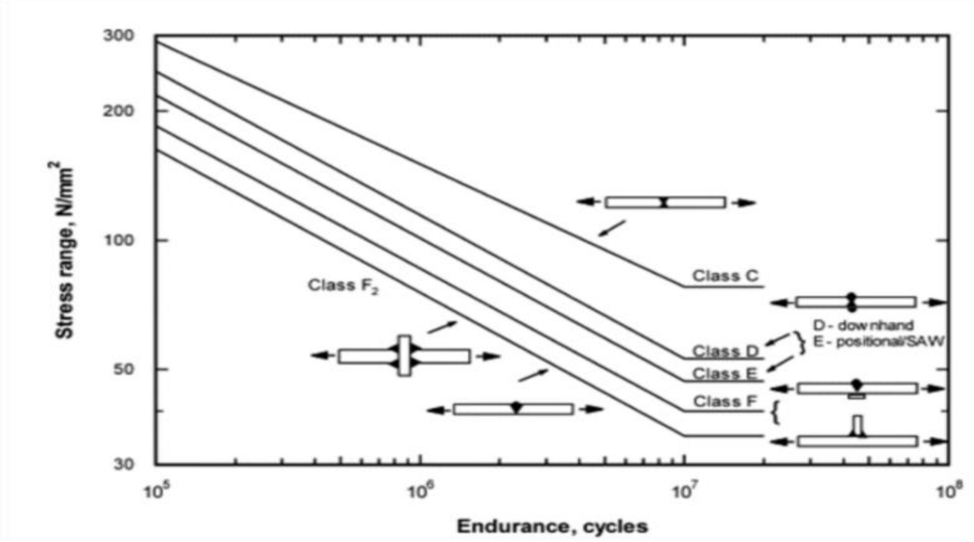


Figure 4. Weld endurance resistance vs type of weld.

Besides the type, the quality of the welding is also important. Figure 5 shows the difference in endurance between sound and defective welds.

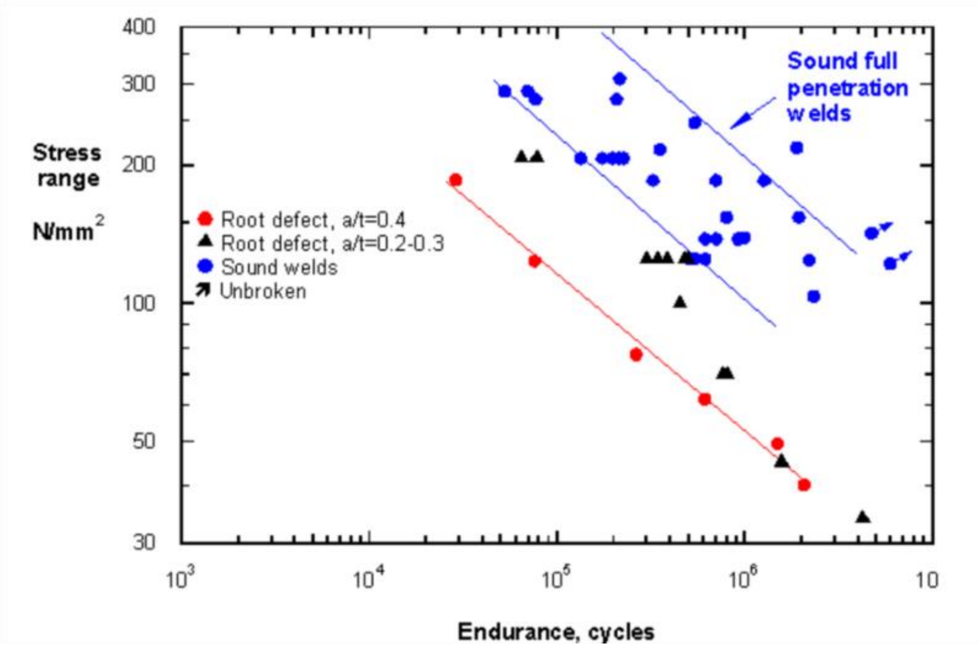


Figure 5. Weld endurance resistance vs weld quality (example).

Modern engineered class pulleys use turbine or T/bottoms for the end discs and automated control atmosphere welding. Older designs used a plate end disc welded to the hub and manual arc welds.

This system is still used successfully on light applications. Although the joint is in a stress concentration area, in lightly loaded pulleys the stresses are below the endurance resistance of the assembly.

Figure 6 shows a heavy pulley with a shaft above 300 mm with such design, where the weld was applied with manual arc. Not surprisingly this pulley failed shortly after a year of operation. 'Savings' in time and cost using a welded hub are irrelevant compared to the loss of reliability and losses due to downtime.

Figure 6. Welded end disc and hub.

Static design wisdom calls for reinforcements to increase the strength of a design, however, when facing fatigue loadings, every weld is a new opportunity for failure and every increase in stiffness creates more stress concentrations. A flexible design with thinner walls is quite often more reliable regarding fatigue than a rigid one.

Figure 7 shows an example of reinforcements that made the problem worse. This relatively light-duty pulley presented cracks in the disc/hub weld. The client decided to install a radial reinforcement as shown on the left side. The result was a crack that grew around the pulley in the interface between the disc and the shell. For the technically orientated, the pictures are quite beautiful, as the crack follows the 3-lobe sinusoidal pattern of the pulley deflection under load, like a lotus flower, that can be seen on a finite element simulation.

Figure 7. Pulley failed at disc/shell interface.

3. BOOM STACKERS

This type of machine is probably the most common in storage yards. An analysis of the operation would show that except for the rotating parts, the main structural components are not subject to large load variations and failures are normally experienced due to corrosion or wear and tear. However, many engineers use the term material fatigue when analysing potential or actual failures.

As an example, Figure 8 shows the finite element model of the mast of a large stacker that was subjected to a design audit by a consultant. The audit report highlighted the stress concentration in the changes of angle of the main columns as a possible cause of fatigue failure in the future.

This finding has two problems. In the first place, the columns are not subject to significant load variations that could cause fatigue.

In the second place, the stress concentration is caused by the geometrical singularity in the model. An inexperienced engineer would reduce the mesh size to analyse the problem, but in the presence of a change of direction, with no radius, the smaller the mesh, the larger the stress at the edge. The real solution would be to simulate the weld and the radiuses involved if it were necessary, which it is not.

This is a 'not so rare' example of lack of understanding by inexperienced designers of the physical phenomena behind a computer simulation. Or as the saying goes: “garbage in, garbage out”.

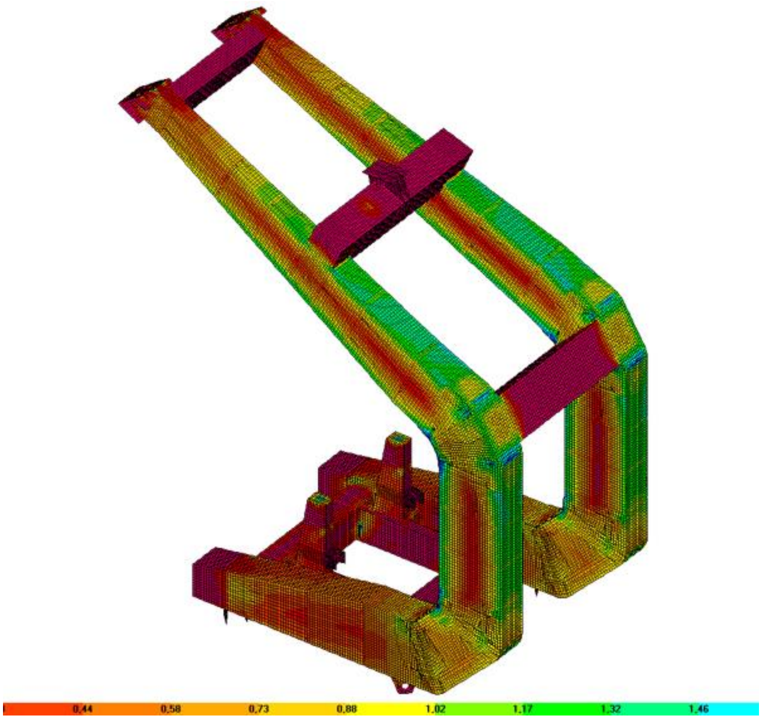


Figure 8. Boom stacker mast FEA model.

A dynamic problem that is relevant to these large and tall machines are seismic loads, especially in countries like Chile and Peru.

Seismic design codes determine the forces in the form of acceleration to be used per location, usage and soil conditions.

Another important factor to be considered is the flexibility of the structure that is associated with the fundamental period. The more flexible the system is, the lower the forces to be considered. Figure 9 shows a typical design response spectrum table that has a factor for structures with natural periods below 0.5 seconds (or a natural frequency above 2 Hertz) and is reduced as the natural period increases.

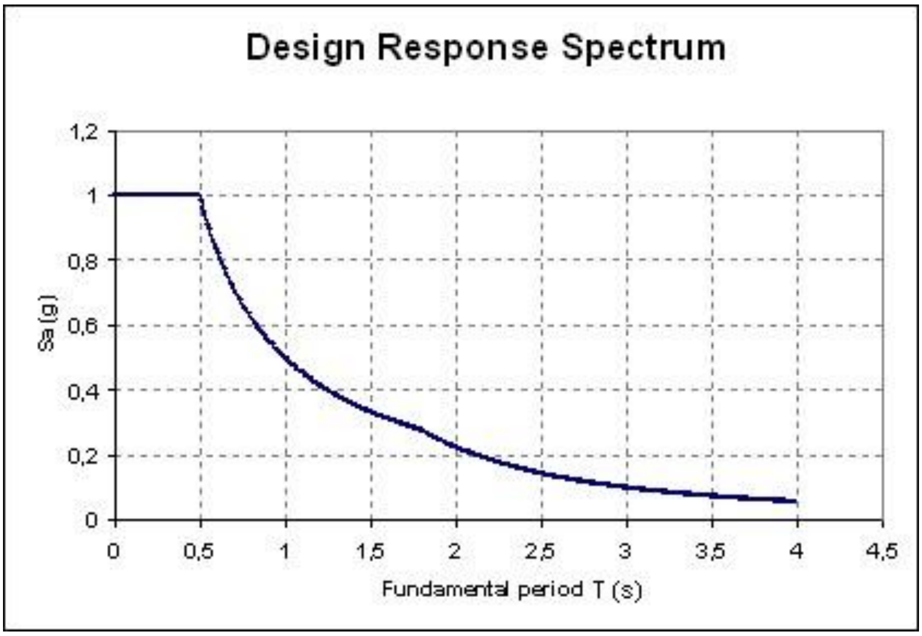


Figure 9. Seismic design factor vs natural period (example).

The first natural vibration mode of a stacker with a long boom with a natural frequency of 0.33 Hz is shown in Figure 10. If this value is considered, seismic forces applied could be reduced by about 90% as compared with a rigid structure. A more in-depth analysis can be done using known seismic spectra from the site in question, using modal type analysis and an appropriate number of natural modes, or a fully-fledged dynamic analysis of the structure. The normal result is that the deeper the analysis, the lower the resultant forces. The seismic codes apply higher safety (or ignorance) factors to simplified design methods.

The common wisdom about seismic design is that it should increase the weight of the structure. This is true if a static approach and an acceleration force without any reduction factor is used. As it is already well known by civil engineers, in seismic design, stiffer is not the same as more resistant. Most modern buildings use flexibility to withstand large seismic loads that include innovative solutions like mounting an entire building on rubber bearings.

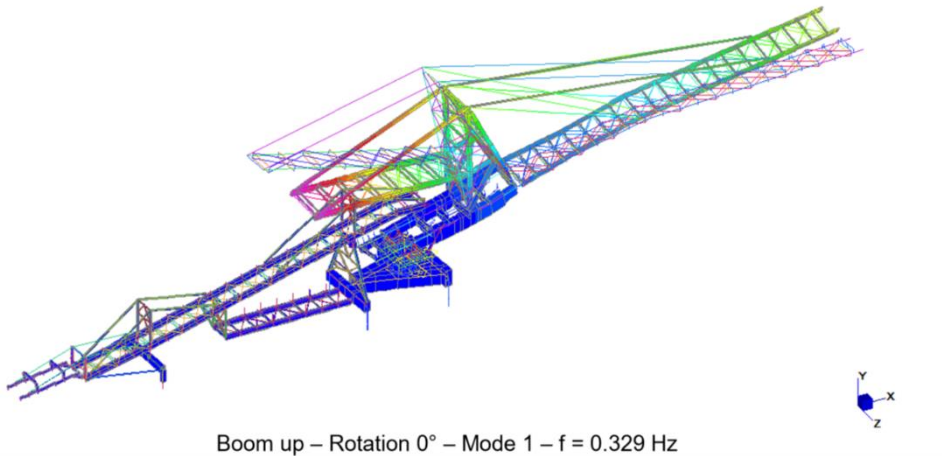


Figure 10. Boom stacker, first natural vibration mode.

4. BRIDGE TYPE RECLAIMERS

Most bridge type reclaimers use scrapers, but for large volumes, sticky and/or abrasive materials, other soutions such as drum reclaimers as shown in Figure 11 are used.

Figure 11. Drum reclaimer.

The drum rotates and has buckets distributed along the shell that take the material from the face of the pile. When each bucket reaches the top, the material falls by gravity onto a belt that runs inside the drum and transfers the material to a yard conveyor.

As it rotates, the drum is subject to alternating stresses while the buckets and the associated openings in the shell present multiple stress concentration points. Old designs from the 60s and 70s had a double skin with even more welds and potential crack problems; the same pattern as some old conveyor pulley designs. Double shells have been replaced today by single skin drums. Even so, cracks appear often and drums have to be replaced periodically, with no comprehensive solution having been found for large capacity systems to date. A conceptual analysis shows that having a large, thin shell drum, with lots of openings that create stress concentrations in a high cycle reverse stress regime is not the best technical solution. Needless to say, this type of machine has lost popularity over the years.

Another design for similar applications, far more popular in modern times, is the bucket wheel bridge reclaimer shown in Figure 12 below. The bucket wheels feed the collecting conveyor while rotating and moving along the bridge to cover the full width of the pile.

Figure 12. Bucket wheel bridge reclaimer.

A mining company bought one of such machines which developed severe vibration and cracking problems. A consultant reccommened remedial action based on static analysis and recommended modifications despite the fact that the problems were most probably of dynamic nature. The machine collapsed shortly thereafter.

The machine was replaced by a new machine, the design of which was based on a succesful lower capacity reclaimer. The new machine presented serious vibration problems and was unable to work at full capacity. A visual assesment of the significant vibrations experienced when the machine crossed the 50% capacity threshold led to the conclusion that one or more of the fundamental frequencies of the structure were being excited. The lack of a dynamic analysis was most probebly the root cause of the problem.

The dynamic behavior of this type of machine was studied by Mr Lucas Assis as part of his master's degree dissertation[4]. He analysed a more modern design supplied by the company he works for with a single bridge with the reclaiming conveyor inside the main girder as shown in Figure 13.

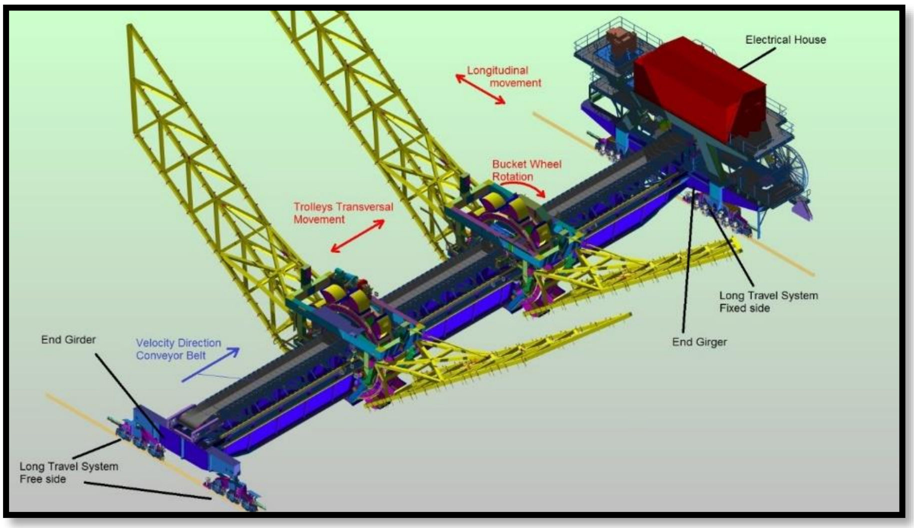


Figure 13. Bucket wheel bridge reclaimer with single bridge.

Mr Assis analysed the operation of the machine and developed parametric formulae to calculate the dynamic forces caused by operation of the bucket wheels moving across the bridge. For illustration purposes, part of the torsional model is shown in Figure 14. The mathematical model allows quick evaluation of the dynamic behavior of the machine. The evaluation can be conducted during basic engineering or even during the bid period and later confirmed in detailed engineering by finite element analysis, although the correlation of the results obtained by analitycal method and FEA is quite good.

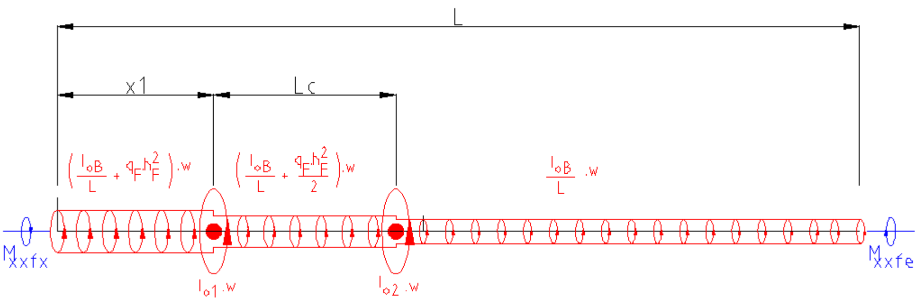


Figure 14. Bucket wheel bridge reclaimer parametric model.

5. CONCLUSIONS

The examples discussed show that dynamic phenomena do not correlate with the methods and standard practices used for static analysis. It is necessary to use the proper tools and do away with the preconceived idea that stronger and heavier is more reliable.

The higher speeds, larger capacities and longer spans more frequently required by more and more demanding clients require analysis to identify potential problems before they arise. This can only be achieved by stepping out of the comfort zone provided by proven, but often limited solutions and examining any conceivable problem areas from a different perspective.

Equally dangerous is the use of static design methods to analyse dynamic problems and the use of computer simulations without proper understanding of the physical problems. Catastrophic failure is a likely result.

The purpose of this paper is to convey the concept that identifying potential dynamic problems is paramount when non-standard designs are used, even in relatively low-tech applications such as materials handling. Using adequate analytical tools require both theoretical and practical skills that are not widespread and are predominantly concentrated in the realm of specialised consultants.

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ABOUT THE AUTHOR

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Thirty years of experience in Engineering, multidisciplinary design, general management, business development, project management, construction, operation and maintenance in the mining and materials handling industries in North and South America, Europe, Africa and Asia.

Mr. Zamorano has taken part in the design and operation of complex conveying systems, both conventional and pipe conveyors, stacking and reclaiming systems, crushing and screening plants, as well as train and ship loading and un-loading systems. This includes several projects that were world's first in capacity, length or configuration at their time.

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