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NUMERICAL MODELLING OF THE DYNAMIC RESPONSE OF THREADBAR UNDER LABORATORY-SCALE CONDITIONS

TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN MINERÍA

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Abstract

New technologies related to the mining have been developed in the last 50 years as the mining industry has expanded in depth. These technological developments have responded not only to production and planning issues but also to problems related to physical phenomena that take place in the field and hinder the mining progress. Prompting research into rockburst events in high stress underground mining has increased internationally in the last few years. Efforts to understand, quantify damage, and mitigate the effects of these events have been the object of many studies carried out by recognized institutes within the mining industry and based on the work done by the Canadian RockBurst Research Program (Cai and Kaiser, 2018; Kaiser et al., 1996).

One study trend has been on how underground excavations are supported and how support systems absorb dynamic impacts. Several researchers have dedicated their efforts to study reinforcement and retainment elements that are part of the support system in an attempt to improve the standard designs widely used and initially conceived for static load resistance.

Institutions such as the CanMet - Mining & Mineral Sciences Laboratories (CanMet-MMSL) of Canada, the Western Australia School of Mines (WASM) and recently the new Dynamic Impact Tester (DIT) of New Concept Mining, have been studying the behaviour of reinforcement and retainment elements under dynamic loads. Their studies have evolved from simply comparing loads to analysing the capacity of support system elements to absorb energy from impacts and deform during the process. Through laboratory-scale testing representative of in-situ conditions, the aforementioned institutions have worked to quantify the deformation and absorption of energy of these elements, resulting in comparative parameters and an adaptable design under dynamic loads. However, laboratory-scale testing involves a high cost in preparation time and validation; hence a limited number of these tests are carried out. Numerical modelling is an alternative that, in addition to complement the results from laboratory testing, should be useful to explain the deformation and energy absorption process. Yi and Kaiser (1994a), Tannant et al. (1995), Ansell (1999; 2005), Thompson et al. (2004), St-Pierre (2007) and Marambio et al. (2018) have modelled the dynamic behaviour of reinforcement elements in laboratory-scale testing centred around load-displacement relationships. The role of grout, however, has not been fully incorporated into those models even though the grout/rockbolt interface has been shown to be the place where the failure occurs to most of the reinforcement elements in situ.

In Chile, the process of developing a new laboratory-scale dynamic testing facility supported by the University of Chile, the Geomechanics Research Center MIRARCO and 'Compañia de Aceros del Pacifico' (CAP), using a mechanism similar to the CanMet-MMSL, has conducted several studies (appended) in which numerical modelling is taken into account as an important part of the process.

In this study, a methodology is proposed to numerically model the process of laboratory-scale dynamic testing of reinforcement elements, i.e. rockbolts plus grouting. Based on the finite difference method, a model was developed, calibrated and verified with a specific focus on the threadbar (also known as rebar or gewibar), which is widely used as rock reinforcement in Chilean underground mining and globally.

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Resumen

Nuevas tecnologías relacionadas a la minería han sido desarrolladas en los últimos 50 años a medida que la industria minera se ha expandido en profundidad. Estos desarrollos tecnológicos han respondido no solo a problemas de producción y/o planificación, sino que también a problemas relacionados a fenómenos físicos que se desarrollan en campo y que impiden el progreso minero. La investigación de eventos de estallidos de rocas (rockburst en inglés) en minería de altos esfuerzos ha incrementado internacionalmente en los últimos años. Esfuerzos por entender, cuantificar el daño y mitigar sus efectos ha sido el objetivo de variados estudios llevados a cabo por instituciones reconocidas dentro de la industria minera y que se basan en el trabajo desarrollado por ‘The Canadian RockBurst Research Program’ (Cai & Kaiser, 2018; Kaiser et al., 1996).

Una tendencia de estudio ha sido desarrollada en cómo las excavaciones subterráneas son soportadas y en cómo los sistemas de fortificación absorben impactos dinámicos. Varios investigadores han dedicado sus esfuerzos en estudiar elementos de refuerzos y retención que son parte de un sistema de fortificación, con el fin de mejorar los diseños estándar ampliamente utilizados e inicialmente concebidos para resistir cargas estáticas. Instituciones como ‘CanMet - Mining & Mineral Sciences Laboratories (CanMet-MMSL)’, ‘Western Australia School of Mines (WASM)’ y recientemente ‘Dynamic Impact Tester (DIT)’ de ‘New Concept Mining’ han estado estudiando el comportamiento de elementos de refuerzo y retención bajo cargas dinámicas. Sus estudios han evolucionado desde una simple comparación de cargas al análisis de la capacidad de absorción de energía de un sistema de fortificación ante impactos dinámicos y su deformación durante el proceso.

A través de ensayos de escala laboratorio representativos de condiciones in-situ, las instituciones mencionadas anteriormente han trabajado para cuantificar la deformación y la absorción energética de estos elementos, resultando en parámetros comparativos y en un diseño adaptable ante cargas dinámicas. Sin embargo, ensayos de escala laboratorio envuelven un alto costo en preparación y validación, por lo tanto, un numero limitado de éstos son llevados a cabo. El modelamiento numérico aparece como una alternativa que, además de complementar los resultados de laboratorio, puede ser utilizada para explicar el proceso de deformación y absorción energética. Yi & Kaiser (1994a), Tannant et al. (1995), Ansell (1999; 2005), Thompson et al. (2004), St-Pierre (2007) y Marambio et al. (2018) han modelado el comportamiento dinámico de elementos de refuerzo en ensayos de escala laboratorio centrados en relaciones de carga-desplazamiento. Sin embargo, el rol de la lechada no ha sido incorporado del todo en estos modelos, aun cuando es la interfaz lechada/perno la que ha mostrado fallar in-situ.

En Chile, el desarrollo de una nueva máquina de ensayos dinámicos a escala laboratorio soportada por la Universidad de Chile, ‘The Geomechanics Research Center MIRARCO’ y la ‘Compañía de Aceros del Pacifico’, la cual utiliza un mecanismo similar a la de CanMet-MMSL, ha conducido variados estudios en donde el modelamiento numérico es tomado como una parte importante del proceso. En este estudio, una metodología es propuesta para modelar numéricamente el proceso del ensayo dinámico de escala laboratorio para elementos de refuerzos, i.e. pernos mas lechada. Basado en el método de elementos finitos, un modelo fue desarrollado, calibrado y verificado con especial énfasis en el perno helicoidal (threadbar, rebar o gewibar en inglés), ampliamente utilizado como elemento de refuerzo en minería Chilena y globalmente.

Acknowledgments

I would like to acknowledge the financial support from the basal CONICYT Project AFB180004 of the Advanced Mining Technology Center (AMTC) and to the project 16CONTEC-65103 ‘*Mejoramiento de las características dinámicas del perno helicoidal para la minimización de interferencias operacionales y riesgo asociado a la ocurrencia de sismicidad inducida por la minería subterránea*’ financed by *Corporación de Fomento de la Producción* (CORFO Innova) and *Compañía de Aceros del Pacífico* (*CAP)*. This Project would not have been possible without their support. In addition, I thank to CODELCO and CODELCOTech for the recognition of this thesis through their ‘Piensa Minería’ grant.

I also would like to acknowledge the interest, assistance and invaluable contribution to the development of this work of Dr. Claudia Gonzalez from MIRARCO Mining Innovation, Canada; Lorena Burgos, Yesenia Marulanda and Jean Louis Azorín from the Geomechanics and Mine Design laboratory of the Advanced Mining Technology Center (AMTC) – University of Chile; and Mrs. Soledad Celis and Mr. Alejandro Muñoz from CODELCO – EL Teniente Mine.

A special acknowledge goes to my advisor, Dr. Javier Vallejos, who has managed to bring out the best in me and challenge me to continually improve in recent years. Thank you for the support provided.

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And finally, I want to especially acknowledge the love, patient and unconditional support of my better half, Mireya Movil. Thank you for all the beautiful time together, the encouragement and the confidence in me. I love you so much!

Dedicated to my grandad who was a father for me
and taught me that keeping your word defines you as a real man…
Wherever you are, this degree also belongs to you…
I did it Manolete!

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CHAPTER 1: BACKGROUND

1.1. Introduction

In the last century, surface ore deposits have decreased over the years hence mining has been forced to expand into depth. New challenges have appeared to be faced for workers of the mining industry. Thus the construction and implementation of new technologies have had to adapt to this new mining context, being more risky as it deepens.

Thereby, one of the most common risks in the last time in underground mines subject to high-stress environments is the rockburst prone. According to Kaiser et al. (1996, updated by Cai and Kaiser in 2018) a rockburst is defined as damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event. The rockburst phenomenon occurs in zones with high-stress anisotropy as the Chilean geological subduction zone in which many mines are placed. The phenomenon represented by a seismic event induced by the stress condition located around underground excavations (Figure a) is visible on the surface of the walls as rock violently ejected. Rockburst, besides being a great hazard for workers, produces support damage/loss at any kind of excavation systems, for example in caving it takes place closuring draw points, in general it causes loss of production and an increase in costs.

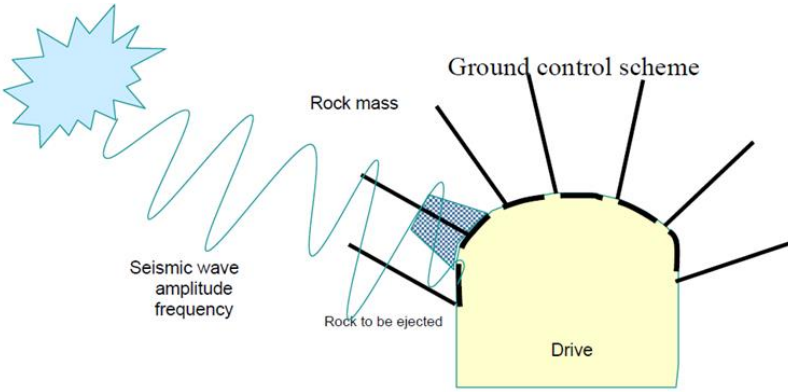

Figure a **Representation of induced seismicity that impacts the wall of an excavation. (Villaescusa et al., 2010)**

Kaiser et al. (1996; Cai and Kaiser, 2018) define the impact types on surface walls of excavations product of induced seismicity as illustrated in Figure b. Then, there are 3 types of impact on the surface. The first one is an abrupt expansion of the rock around the excavation defined as strainburst or rock bulking; the second type is related to the impact velocity of the wave when is transferred to the adjacent rock resulting in an ejected rock; and the third type takes place when blocks of rocks fall product of vibration.

Due to the above, in the last 30 years several researchers (Doucet and Voyzelle, 2012; Li and Doucet, 2012; Player and Cordova, 2009; Player et al., 2009; Villaescusa, 2012) have been making efforts to control the effects of rockburst phenomenon and decrease the hazard for workers and excavations. In this matter, efforts have been made to determine some type of excavation support that absorbs the energy released by the induced seismicity without failure in the process, improving the classical systems of static support.

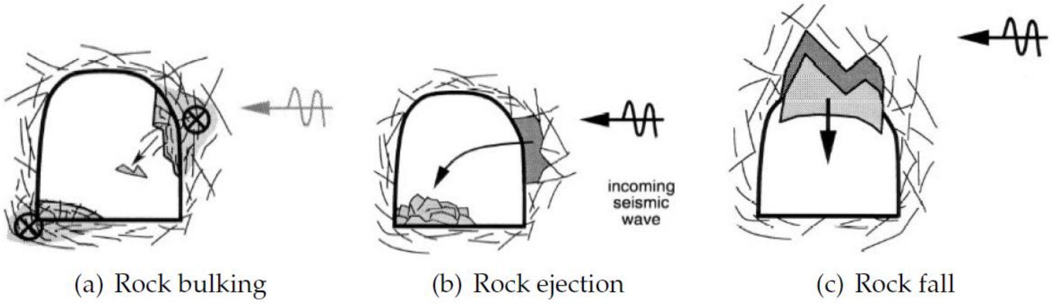

Figure b Types of rockburst damage product of induced seismicity. (Kaiser et al., 1996)

Studies and testing programs have been carried out to determine the correct support system to be used against rockburst phenomenon. Framed in this context, the proposal research delves in the reinforcement design to resist dynamic loads, specifically in the threadbar (rebar or gewibar), commonly used in Chilean underground mining as reinforcement element. Thereby, laboratory-scale dynamic test results from testing facilities of institutions as CanMet-MMSL (Yi and Kaiser, 1992) or WASM (Player et al., 2004) will be replicated in a numerical model in order to know and improve the behaviour of threadbar under dynamic loads.

1.2. Hypothesis

Recent research on reinforcement elements at laboratory-scale conditions has focused on how these elements can absorb dynamic impacts, lengthen and/or slip and possibly fail during the process (Doucet and Voyzelle, 2012; Li and Doucet, 2012; Player and Cordova, 2009; Player et al., 2009; Villaescusa, 2012). Then a 'characteristic footprint' (laboratory-scale response) for a specific type of reinforcement element is obtained. The laboratory-scale response (reaction curve) reports design parameters such as elastic stiffness, yielding limit, ultimate strength, and/or ultimate displacement (lengthening).

Due to the costs in time preparation and validation of these laboratory-scale dynamic tests only a few tests can be performed for a specific type of reinforcement element. Therefore, only based on the limited dynamic test results, it may be difficult to provide an improvement of the characteristics that define a specific type of reinforcement element.

However, numerical modelling appears to be a tool that complements the laboratory-scale response of a specific reinforcement element, leading to a better understanding of the behaviour of these elements under dynamic loads.

Considering the dynamic response of the threadbar (rebar or gewibar) used as reinforcement element, a first approach to improve its performance is related to the geometric characteristics of the element. In theory, increasing the diameter or the length of the threadbar would result in an increase of the absorption capacity and therefore in its 'characteristic footprint'.

The second approach to improving its performance is related to the material from which the threadbar is made, hence the steel grade. A particular steel grade can be related with a particular behaviour in terms of strength and plasticity, then changing the steel grade of the element would result in an improvement of its dynamic response or its 'characteristic footprint'.

1.3. Thesis Objectives

The objectives of the thesis are detailed below:

1.2.1. General Objectives

- Study and comprehension of the dynamic response of threadbar used as reinforcement element in Chilean mining under laboratory-scale conditions through numerical modelling.

1.2.2. Specific Objectives

- To focus the study on threadbar (rebar or gewibar) response when it is used as reinforcement element.
- To do parametric analysis of geometry variables and materials used in the laboratory-scale dynamic test.
- To integrate simulations to the model through randomization.
- To propose improvements to the threadbar design.
- To develop a numerical modelling through the finite element software FLAC^{3D} (Itasca Consulting Group, 2012).

1.4. Methodology

In order to achieve the objectives of this research the following methodology was implemented:

1. Compilation of dynamic testing results from literature for threadbar carried out by CanMet-MMSL and WASM.
2. Construction of a physical model representative of the dynamic test that considers the interaction among threadbar, cement grout and the encapsulating steel tube in FLAC^{3D}.
3. Calibration of the numerical model with dynamic testing results from literature.
4. Parametric analysis of the dynamic test through the calibrated numerical model.
5. Verification of the calibrated numerical model with a new result from literature considering new geometric and material variables.
6. Proposal of improvements to the design of threadbar for use as reinforcement element in underground mining subject to dynamic loads.

1.5. Thesis Contents

This research resulted in the following articles:

- **Article 1: "Numerical modelling of dynamic testing of rock reinforcement used in underground excavations"**
  Presented at the Fourth International Symposium on Block and Sublevel Caving held in Vancouver, Canada, October 2018. This paper mainly describes the background of the dynamic testing facilities, a development of a physical model that represents the problem and a first calibration of the numerical model with literature results. This article is available online (https://papers.acg.uwa.edu.au/p/1815_60_Marambio/) and is not included in this thesis.

- **Article 2: "Numerical modelling of the dynamic response of threadbar under laboratory-scale conditions"**
  Article sent to the International Journal of Tunnelling and Underground Space Technology (ELSEVIER), 2019. This paper includes and complements the first article, which describes in detail the entire process of numerical modelling, the obtained results, a discussion and the conclusions of design and improvements focused on threadbar. Therefore, the research illustrates: the development of the physical model in the finite element software, the expansion of the calibration process, a parametric analysis and the verification of the model. The paper was recently published and is available online: https://doi.org/10.1016/j.tust.2019.103263

CHAPTER 2: ARTICLES

Following, only the second article (ISI paper) will be presented. This paper includes and complements the work presented in the first article. For more details, article 1 is available online: https://papers.acg.uwa.edu.au/p/1815_60_Marambio/

2.1. Article 2:

Numerical modelling of the dynamic response of threadbar under laboratory-scale conditions

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Abstract

The development of mining and underground excavations under high stress conditions, where the occurrence of seismic events may induce sudden energy release, has generated new challenges and additional research related to the dynamic response of reinforcement systems. To ensure safety of underground excavations, the development of new reinforcement elements able to resist dynamic events and yielding during the loading process has advanced in the last 30 years as a result of research studies and testing programs carried out by recognized institutions. The execution of these testing programs involves a considerable time and requires validation. In Chile, the development of a new laboratory-scale dynamic test facility has required several studies in which numerical modelling is considered as an important part of the design process. This paper presents the implementation and results of a numerical model used to simulate the dynamic response of threadbar under laboratory-scale test conditions. A comprehensive calibration of the numerical model using the results of laboratory-scale dynamic tests available from the literature is presented. The continuous and split configurations for the encapsulating tube are tested and compared. A parametric analysis is performed with the calibrated model. The verification of the model is established with an additional laboratory-scale result not considered in the calibration process. A summary of the results in terms of the dissipated energy and the maximum displacement is presented. The results indicates a linear trend between the dissipated energy and the maximum displacement, and a significant improvement of the dynamic response of threadbar when the steel grade or the diameter of the rockbolt is increased.

Keywords: *Dynamic tests, Reinforcement elements, Numerical modelling, Rockburst, High stress conditions, Underground excavations*

1. Introduction

In the last century, as the mining industry has expanded in depth, new related technologies have been developed. These technological developments have responded not only to production and planning issues but also to problems related to the physical phenomena that take place at the field and hinder the mining progress. Prompting research related to mining seismicity and rockbursting under high stress conditions has increased internationally in the last few years. Efforts to understand, quantify damage, and mitigate the effects and occurrence of these events have been the object of many studies carried out by recognized institutes within the mining industry and based on the work done by the Canadian RockBurst Research Program (Cai and Kaiser, 2018; Kaiser et al., 1996). One study trend has been on how underground excavations are supported and how support systems absorb dynamic impacts. Several researchers have dedicated their efforts to study reinforcement and retainment elements that are part of the support system in an attempt to improve the standard designs widely used and initially conceived for static load resistance.

Institutions such as the CanMet - Mining & Mineral Sciences Laboratories (CanMet-MMSL) of Canada, the Western Australia School of Mines (WASM) and recently the Dynamic Impact Tester (DIT) of New Concept Mining, have been studying the behaviour of reinforcement and retainment elements under dynamic loads. Their studies have evolved from simply comparing loads, to analyze the capacity of support element systems to absorb energy from dynamic impacts and deform during the process. Through laboratory-scale tests representative of in-situ conditions, the aforementioned institutions have worked to quantify the deformation and energy absorption of these elements, resulting in comparative parameters and an adaptable design under dynamic loads. However, laboratory-scale tests involve a high cost in preparation time and validation; hence a limited number of these tests are carried out. Numerical modelling is an alternative that may complement the results from laboratory tests, and can be useful to explain the deformation and energy absorption process. Yi and Kaiser (1994a), Tannant et al. (1995), Ansell (1999; 2005), Thompson et al. (2004), St-Pierre (2007) and Marambio et al. (2018) have modelled the dynamic behaviour of reinforcement elements under laboratory-scale tests related to the load-displacement relationship. The role of grout has not been fully incorporated into these models, even though field observations have shown that the grout/rockbolt interaction is part of the failure process.

In Chile, a new laboratory-scale dynamic test facility, supported by the University of Chile and the Geomechanics Research Center MIRARCO, is under development. This frame uses a mechanism similar to the CanMet-MMSL facility. As a part of the design process several studies related to numerical modelling have been considered. In this study, a methodology is proposed to numerically model the dynamic response of reinforcement elements under laboratory-scale test conditions. The model was developed with a specific focus on the dynamic response of threadbar (also known as rebar or gewibar), which is widely used as rock reinforcement in Chilean underground mining and globally.

2. Problem conceptualization

At the present time, there are mainly two laboratory facilities, recognized by the industry, for testing reinforcement elements under dynamic loading conditions. The first started between 1992 and 1994 by Yi and Kaiser under the Canadian Rockburst Research Program (CanMet-MMSL facility), and the second, started in 2004 by Player and Thompson with the support of 'Minerals & Research Institute of Western Australia' (WASM facility). The difference between the CanMet-MMSL dynamic testing facility and the WASM dynamic testing facility lies in the principle used for their conceptual model and experimental tests.

The CanMet-MMSL facility is based on the energy transfer principle, whereas the WASM facility is based on the momentum transfer concept. However, it should be considered that the two facilities physically involve both principles depending on how the problem is addressed. In this sense, the CanMet-MMSL facility transforms potential energy into kinetic energy through the fall of a mass from a given height that impacts the lower end of a rockbolt embedded in a pipe with grout causing deformation and possible failure (simulating the in-situ conditions). On the other hand, the WASM dynamic facility operates by measuring the effects of the fall of a complete system including a beam, the reinforcement, and a loading mass. The system falls freely to a point where it is abruptly stopped by buffers. Under this condition, the rockbolt continues to move and could lengthen and/or slip and possibly fail. Figure 1a shows the CanMet-MMSL dynamic testing facility set-up, while Figure 1b shows the dynamic testing facility developed by WASM. It is worth mentioning that recently, the DIT facility of New Concept Mining (Crompton et al., 2018), the same CanMet-MMSL's principle applies, expanding the catalogue of laboratory-scale dynamic testing facilities with new tests configurations and reinforcement elements.

Furthermore, it is important to consider that depending on the requested response of the rock reinforcement, there are two main sample configurations for the dynamic test. The first is the conventional sample configuration, where a rockbolt sample is embedded in a continuous steel pipe with grouting material simulating the field conditions. The second is the split-tube sample configuration, where the rockbolt sample is embedded with grouting material in a split steel pipe that simulates a discontinuity in the rock mass. Both configurations are shown in Figure 2.

The development of the numerical model described in this communication has been motivated by two facts: on the one hand, in Chile the development and construction of a future laboratory-scale dynamic testing facility supported by the University of Chile and MIRARCO with a mechanism similar to the CanMet-MMSL. On the other hand, several authors have questioned the effects of dynamic loads on rock reinforcements (Doucet and Gradnik, 2010; Doucet and Voyzelle, 2012; Li and Doucet, 2012; Wu et al., 2010) and those questions also inspired the numerical model described in Section 3.3. Most importantly, the threadbar response was selected in this first approach because of the urgent need to improve its performance under the dynamic conditions found in Chilean underground mining. Regrettably, due to restricted availability of threadbar results from CanMet-MMSL, only a limited comparison and calibration of results could be made with laboratory-scale dynamic test results from WASM which are available in the literature (Player and Cordova, 2009; Player et al., 2009). Thus, the model designed in this paper is focused mainly on the methodology and implementation through the finite element method. The model will be further discussed in Section 5.

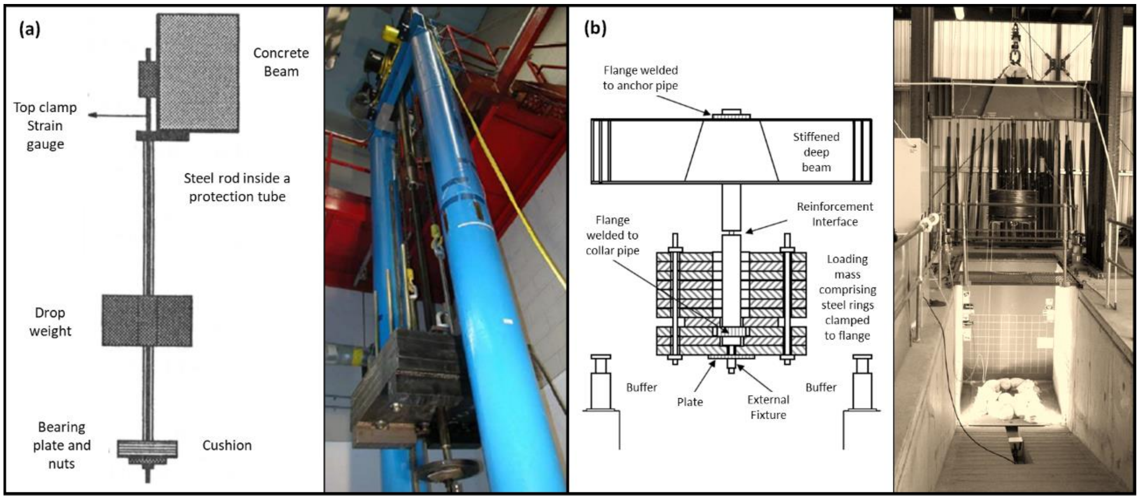

Figure 1 (a) Set-up of the dynamic testing facility at CanMet-MMSL (After Yi and Kaiser, 1994b; 1992). (b) Set-up of the dynamic testing facility at WASM (After Player et al., 2008; 2004)

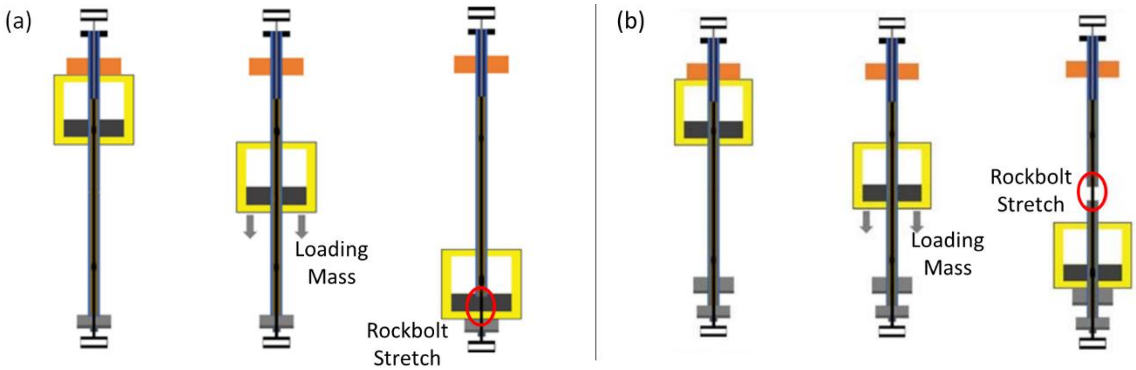

Figure 2 Sample configurations for the dynamic test. (a) Continuous tube (conventional). (b) Split-tube (Crompton et al., 2018)

3. Numerical modelling

In recent years, various efforts have been made to numerically represent the behaviour of dynamic tests for reinforcement elements used in underground excavations. Two approaches have been widely used within the computational mathematical area for the representation of this problem, the lumped-mass models and the dynamic deformation models in a continuum media.

The lumped-mass models describe the reinforcement elements as discrete masses array in series connected to each other by springs and dampers, and have been used in models proposed since the beginning of dynamic studies programs for reinforcement elements. Tannant et al. (1995) were early proponents of such a model for the CanMet-MMSL test facility within the Rockburst Research Program of Canada. Thompson et al. (2004) used a similar model to describe reinforcement behaviour in the WASM test facility. The most recent work that involved this approach has been presented by St-Pierre (2007), in which the cone bolt dynamic behaviour obtained at CanMet-MMSL facility was numerically modelled.

Dynamic deformation models use discrete elements to describe the behaviour of the reinforcement element as a continuous and deformable medium. In this approach, stress and deformation waves characterize the material behaviour in the elastic and plastic ranges through the propagation of the discretized elements in the medium. With this approach, Ansell (1999, 2005) reviewed representative models of response under dynamic loads. Also, Yi and Kaiser (1994a) used these models to describe the wave behaviour inside the reinforcement elements.

It is important to note that dynamic deformation models and lumped-mass models have different objectives. The dynamic deformation models are more detail-oriented and focus on resolving problems related to specific components of a system, whereas lumped-mass models are more global and produce solutions involving the complete system. The approach used in this paper corresponds to the lumped-mass, in which the reinforcement element is represented by secondary elements (segments) joined together by nodes, as shown later in Figure 4b. The lumped-mass approach was chosen based on a more global objective to replicate the combined response of the rockbolt and the grout in the dynamic testing facilities, rather than to describe the behaviour of the internal waves in the elements.

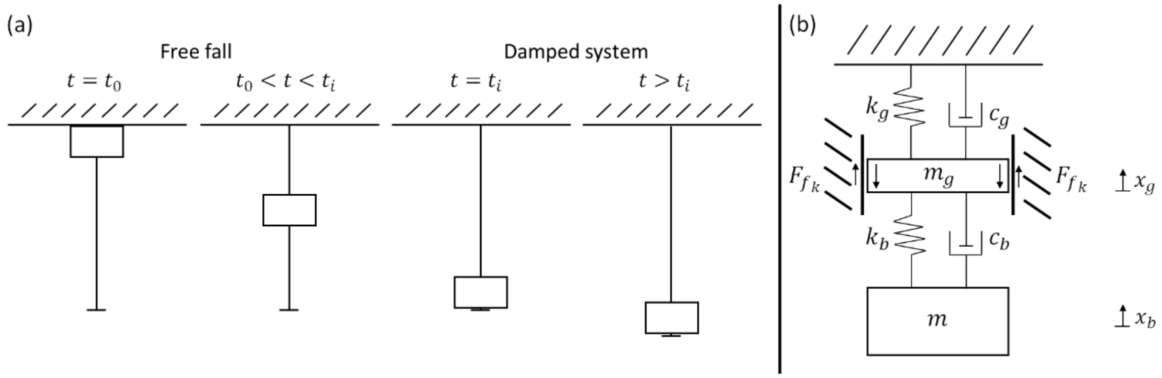

Figure 3 **(a) Two step problems of the model at different moments of time. (b) Free-body diagram of the model (After St-Pierre, 2007)**

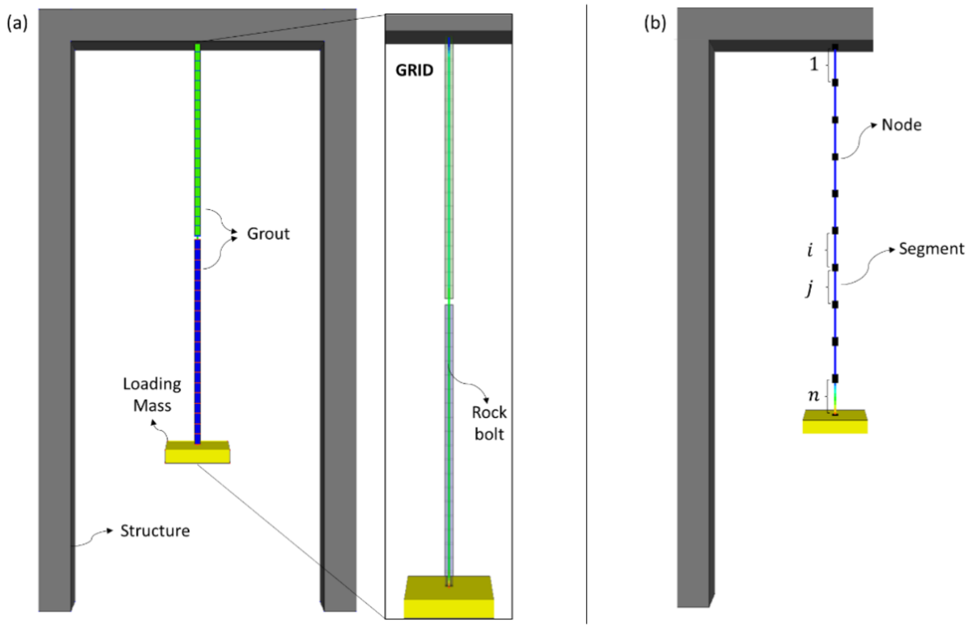

Figure 4 (a) Model built in FLAC^{3D} Software. (b) Reinforcement element represented by segments joined by nodes

3.1 Governing equations of motion

Diverse models that characterize the dynamic structures under certain applied force use resolution schemes in which the whole system is simplified and described through a damped oscillator. In this sense, the equations that describe the process and their solution are well known. However, the complexity of these systems lies in how the conditions of stiffness and damping are applied, incorporating difficulties in the representation of the real conditions of the problem.

To solve the numerical model, the system is divided into a two-step problem. The first problem is described by the free falling of the mass used in the dynamic test until the impact with the plate (damping cushion in the current test) at a particular time (t_i). The second, is a numerical problem that takes place after the moment of impact (t_i), when the mass begins to move along with the rockbolt, stretching it or sliding it until a possible failure. A scheme of the problem in the numerical model is illustrated in Figure 3a, where the mass begins to fall freely at time t_0 until the impact at time t_i, at this time the mass with the rockbolt begins to behave as a damped oscillatory system. After the impact of the mass with the plate, the model is characterized as a simplified problem by the free-body diagram of Figure 3b. Therefore, the system can be represented by two differential equations, the first one describes the motion of the rockbolt and the second one the motion of the grout, as presented in Equations (1) and (2), respectively. A similar scheme was shown by St-Pierre (2007) in the development of a model for the cone bolt reinforcement element.

$$m\ddot{x}_b + c_b(\dot{x}_b - \dot{x}_g) + k_b(x_b - x_g) - F_{f_k} + mg = 0 \tag{1}$$

$$m_g\ddot{x}_g - c_b(\dot{x}_b - \dot{x}_g) - k_b(x_b - x_g) - c_g\dot{x}_g - k_g x_g + F_{f_k} = 0 \tag{2}$$

Where m is the loading mass used in the dynamic test; m_g is the grout mass; g is the gravitational constant; k_b and k_g are the stiffness of rockbolt and grout, respectively; c_b and c_g are the viscous damping of rockbolt and grout, respectively; x_b and x_g are the displacement of rockbolt and grout, respectively; $\dot{x}_b$ and $\dot{x}_g$ are the velocity of rockbolt and grout, respectively; $\ddot{x}_b$ and $\ddot{x}_g$ are the acceleration of rockbolt and grout, respectively; and F_{f_k} is the friction force representing the contact between rockbolt and grout. Note that the mass of the rockbolt (m_b) in Equation (1) and grout weight ($m_g g$) in Equation (2) are negligible when compared with the loading mass from the dynamic test (m). The loading mass from the dynamic test is approximately 200 times higher than the mass of the rockbolt.

The stiffness of the rockbolt and the grout shown in Equations (1) and (2) are approximated by their equivalent stiffness for oscillatory systems connected in series (Rao and Yap, 2011). Furthermore, the viscous damping of the rockbolt and the grout shown in Equations (1) and (2) are proportional to their respective masses and stiffness, commonly known as classical damping of Rayleigh (1877), described by Equation (3).

$$
\begin{gathered}
c_b = a_{0_b} m_b + a_{1_b} k_b \\
c_g = a_{0_g} m_g + a_{1_g} k_g \\
a_{0_b} = 2\omega_{1_b}\xi_{1_b} - a_{1_b}\omega_{1_b}^2 \qquad a_{1_b} = \frac{2(\omega_{2_b}\xi_{2_b} - \omega_{1_b}\xi_{1_b})}{\omega_{2_b}^2 - \omega_{1_b}^2} \\
a_{0_g} = 2\omega_{1_g}\xi_{1_g} - a_{1_g}\omega_{1_g}^2 \qquad a_{1_g} = \frac{2(\omega_{2_g}\xi_{2_g} - \omega_{1_g}\xi_{1_g})}{\omega_{2_g}^2 - \omega_{1_g}^2}
\end{gathered}
\tag{3}
$$

Where a_{0_b} and a_{0_g} are mass proportional damping coefficients of rockbolt and grout, respectively; a_{1_b} and a_{1_g} are stiffness proportional damping coefficients of rockbolt and grout, respectively; m_b and m_g are the mass of rockbolt and grout, respectively; ω_{1_b} and ω_{2_b} are the first and second normal mode of vibration for rockbolt, respectively; ω_{1_g} and ω_{2_g} are the first and second normal mode of vibration for grout, respectively; ξ_{1_b} and ξ_{2_b} are the first and second damping ratio of rockbolt, respectively; and ξ_{1_g} and ξ_{2_g} are the first and second damping ratio of grout, respectively.

3.2 Materials influence

The rockbolt properties under static conditions are well established from the manufacturer catalogues. However, it is well known that steel changes its yield limit and ultimate strength under dynamic loading conditions. According to Malvar and Crawford (1998), these magnitudes can be estimated by the elastic properties of steel scaled through a dynamic increase factor as shown in Equation (4).

$$DIF = \left(\frac{\dot{\varepsilon}}{10^{-4}}\right)^{\alpha}$$

$$\alpha_{f_y} = 0.074 - 0.040\frac{f_y}{414} \tag{4}$$

$$\alpha_{f_u} = 0.019 - 0.009\frac{f_y}{414}$$

Where DIF is the dynamic increase factor; $\dot{\varepsilon}$ is the strain rate; f_y is the yield limit of steel under static conditions in MPa; and α_{f_y} and α_{f_u} are coefficients for the yield limit and ultimate strength of the steel, respectively. Malvar and Crawford (1998) recommend the use of DIF for steel grades with static yielding loads from 290MPa to 710MPa and strain rates from 10^{-4} s^{-1} to 225 s^{-1}. These values are consistent with the values obtained in the numerical model simulations under the dynamic testing conditions. In addition, Li et al. (2019) and St-Pierre (2007) used the DIF approximation to empirically estimate the yielding and ultimate strength of rockbolts under dynamic loads in a double shear configuration and for the conebolt tested at the CanMet-MMSL facility, respectively.

The normal modes of vibration for rockbolts can be approximated from a steel bar embedded at one extreme (Den Hartog, 1985), as illustrated in Equation (5).

$$\omega_{n_b} = \frac{\mu_n}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \tag{5}$$

Where ω_{n_b} is the n-normal mode for the rockbolt; L is the length of the rockbolt; ρ is the density of the rockbolt; E is the Young's modulus of the rockbolt; I is the moment of inertia of the rockbolt; A is the cross area of the rockbolt; and μ_n is an empirical coefficient for each mode ($\mu_1 \cong 3.52$ and $\mu_2 \cong 22$).

The grout is a more difficult material to model given its less homogeneous and less isotropic nature. Hyett et al. (1992) studied the static behaviour of the grout for cable bolts by considering the results of pull-out tests. Through these tests, it was found that the properties of the grout depend mainly on the ratio between water and cement, the embedding length, and the applied radial confinement. At laboratory-scale tests the borehole is simulated through a steel pipe, and the radial stiffness (Hyett et al. 1992) is described by Equation (6).

$$k_{r_p} = \frac{2E_p}{(1+v_p)}\left\{\frac{d_o^2 - d_i^2}{d_i\left[\left(1-2v_p\right)d_i^2 + d_o^2\right]}\right\} \tag{6}$$

Where k_{r_p} is the radial stiffness of the encapsulating pipe; v_p is the Poisson's ratio of the encapsulating pipe; E_p is Young's modulus of the encapsulating pipe; d_i and d_o are the inner and outer radius of the encapsulating pipe, respectively.

On the other hand, to estimate the shear stiffness k_g and the cohesive strength c_g of the grout, the formulations of St John and Van Dillen (1983) were used, as shown in Equation (7).

$$k_g \cong \frac{2\pi G_g}{10\ln\left(1 + 2t/D\right)} \tag{7}$$

$$c_g = \pi(D + 2t)\tau_l Q_B \qquad \Rightarrow \qquad c_g \approx \pi(D)\tau_l Q_B$$

Where G_g is the shear modulus of the grout; $D + 2t$ represents the borehole diameter (where D is the diameter of the rockbolt and t is the annulus thickness of the grout), equivalent to d_i; τ_l is the shear strength of the grout, estimated as one half of the uniaxial compressive strength; and Q_B is the bonding quality of grout and rock mass (encapsulating pipe in this case), equal to 1 for the perfect bond. Note that since the interface of interest is between the grout and the rockbolt, the cohesive strength equation is evaluated for D instead of $D + 2t$. This is consistent with the in-situ experience where the failure of most reinforcement elements occurs in the rockbolt/grout interface rather than at the grout/rock interface.

Finally, the normal modes of vibration for the grout are determined by the eigenvalues of the modal matrix, where the values of the normal modes are extrapolated to a damping system, as illustrated by Nilsson (2009).

3.3 Implementation of the damped model

To ensure that the damped model described by the Equations (1) and (2) has been implemented into the finite difference software FLAC^{3D} (Itasca Consulting Group, 2012), a conceptualized scale structure was constructed following the design of the future laboratory-scale dynamic testing facility to be built in Chile, very similar to the CanMet-MMSL's. In this context, the components of the numerical model can be summarized as follows:

- The threadbar is represented in the model by a discretized cable structural element that responds to the tension through a perfectly plastic constitutive model.
- A grid that envelops the threadbar and represents the grout and the steel pipe in which the rockbolt is inserted into the laboratory-scale dynamic tests. The grout behaviour is taken into account through this grid in the numerical model.
- A loading mass represented by a geometric element, which is released in a free fall condition along the threadbar before the impact. After the impact the loading mass is joined to the final discretized element simulating the dynamic impact generated at the laboratory-scale test.
- A structure that supports the whole system in which the dynamic test is performed.
- In the case of laboratory-scale dynamic tests with the split-tube configuration, the grid that represents the grout and the encapsulating pipe is divided in two segments.

Figure 4 shows the scale of the model constructed in FLAC^{3D}.

To characterize the encapsulating effect of the pipe, a time dependent routine in FISH (FLAC^{3D} programming language) was implemented. This routine considers the radial deformation of the grid (that represents the grout and the steel pipe) Δr_p^j at a time t_j and applies an equivalent radial compression $\sigma_{r_p}^j$, proportional to k_{r_p}, at a time t_{j+1} as given by Equation (8).

$$\sigma_{r_p}^{j} = k_{r_p} \Delta r_p^{j} \tag{8}$$

Figure 5 illustrates the process considered for applying the radial compression to the grid that represents the grout in the numerical model.

Note that the model available in FLAC^{3D} for the grout material (St. John and Van Dillen, 1983) assumes an elastic-perfectly plastic behaviour. Some corrections have been made by Bin et al. (2012) to the cohesive strength and friction angle for numerical purposes of pull-out tests, but these corrections were not considered in the numerical model.

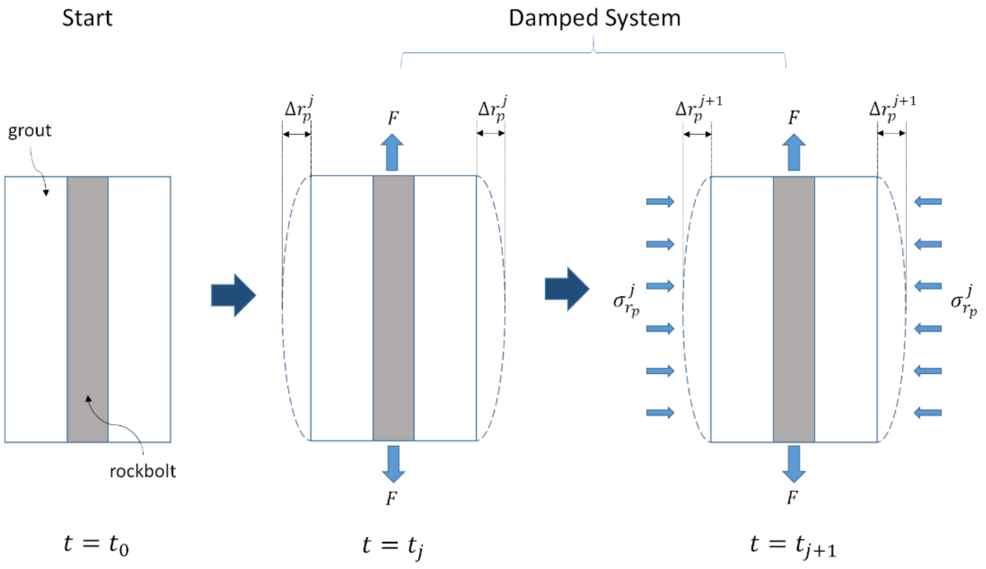

Figure 5 Scheme of application of the equivalent radial compression to the grid in FLAC^{3D} Software

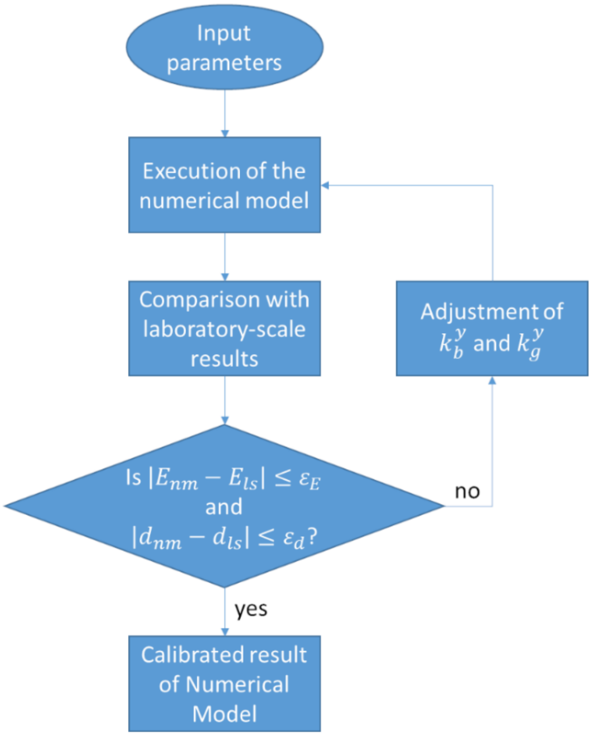

Figure 6 **Diagram of the calibration of the numerical model process**

The entire numerical model is solved by an iterative numerical method – explicit in time combined with an unbalanced force criteria. In this process the results of the numerical model are compared with the laboratory-scale results from the literature in terms of the displacement and dissipated energy, adjusting the initial stiffness of rockbolt and grout at the yielding point (k_b^y and k_g^y, respectively) during its execution if necessary. For this purpose, the displacement of the reinforcement as a result of the numerical model d_{nm} and its respective dissipated energy E_{nm} are compared with the same results (d_{ls} and E_{ls}, respectively) from the laboratory-scale dynamic tests. A target tolerance for the displacement ε_d and dissipated energy ε_E is defined. Equation (9) shows the relationship between these variables.

$$\begin{aligned} |E_{nm} - E_{ls}| &\leq \varepsilon_E \\ |d_{nm} - d_{ls}| &\leq \varepsilon_d \end{aligned} \tag{9}$$

It is has to be recognized that longer computational times are required to achieve the convergence of the numerical model when a smaller ε value is used. In addition, the stiffness of the rockbolt and grout at the yielding point were reduced by increments at each step time from its initial value (k_b and k_g), respectively. A diagram of the process of resolution is shown in Figure 6.

Summarizing, the numerical model considers the following input parameters. For the rockbolt: length, diameter, the yield and ultimate load of the steel under static conditions, the modulus and the stretching limit (specified by the manufacturer) under static conditions. For the grout: the modulus and uniaxial compressive strength under static conditions. For the dynamic test: the loading mass, and the inner and outer diameter of the encapsulating tube. On the other hand, in the continuous tube configuration the monitoring point is located between the loading mass and the lower end of the encapsulating tube. Whereas, in the split-tube configuration the monitoring point is located at the discontinuity of the encapsulating tube.

Figure 7a shows three temporal stages of the dynamic test model for the continuous tube configuration, whereas Figure 7b shows the same three temporal stages of the dynamic test model for the split tube configuration. This figure demonstrates how the numerical model represents the scheme shown in Figure 3a.

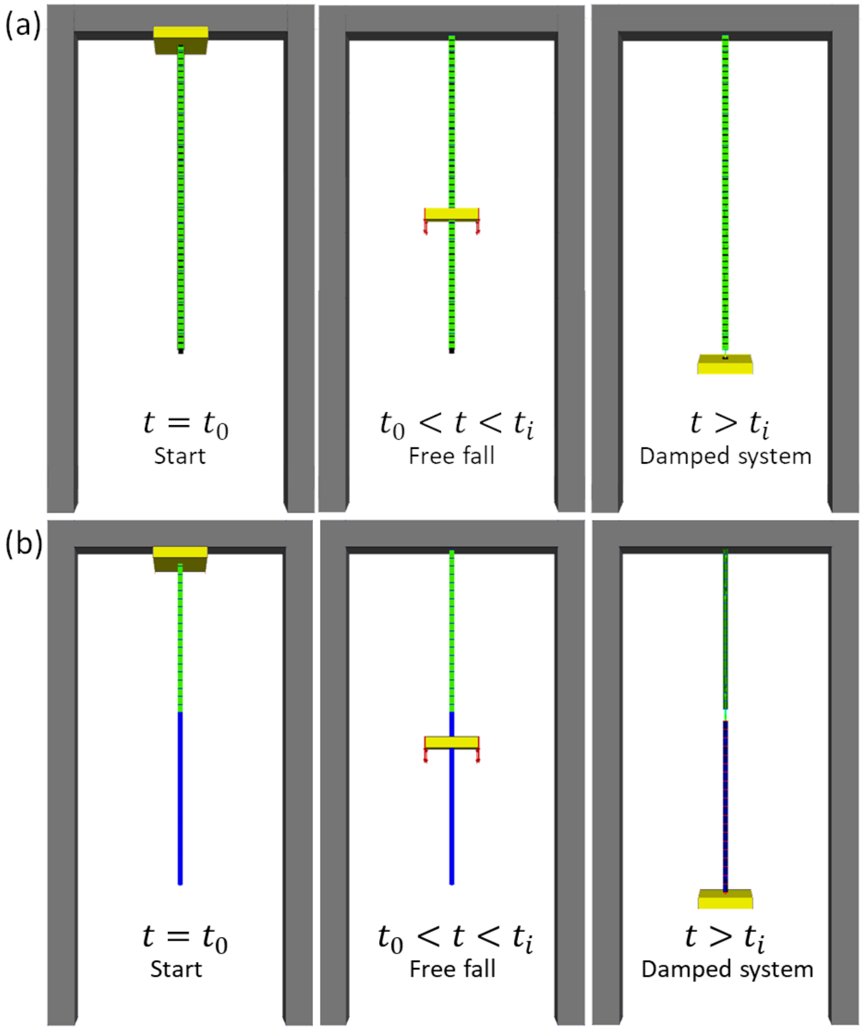

Figure 7 **Model implemented in FLAC^{3D} Software. (a) Continuous tube configuration. (b) Split-tube configuration. From left to right three temporal stages of the numerical model simulation**

4. Results

The desired result is to replicate the dynamic response of reinforcement elements under laboratory-scale test conditions, in particular for the threadbar. In this section, the calibration of the model, a parametric analysis and the verification of the model are presented.

4.1 Calibration of the model

Figure 8a, b and c show the comparison of the load-displacement curve obtained by the model simulations and the laboratory-scale dynamic test results from the WASM frame for the threadbar (Player et al. 2009; Player and Cordova, 2009) with a 2.3 m, 3.2 m and 3.0 m rockbolt length, respectively. In these graphs, the similarity between the numerical model and the laboratory testing results can be appreciated. The input parameters and coefficients used in the modelling are summarized in Table 1. In addition, Figure 9a and b illustrate, as an example, the numerical results of the force, displacement, grout state and cable state profiles of a 3.2 m rockbolt length sample at the final time stage of the model simulation (when equilibrium has been reached) for a continuous tube and split-tube configurations, respectively.

Figure 8d shows the comparison between the numerical model results for a continuous tube and a split-tube configurations, with the laboratory-scale dynamic test results for threadbar from the WASM facility for a 3.2 m rockbolt length**.** Note that the difference between the dynamic response of the split-tube and the continuous tube configurations is negligible. The results differ mainly in the monitoring point along the reinforcement element.

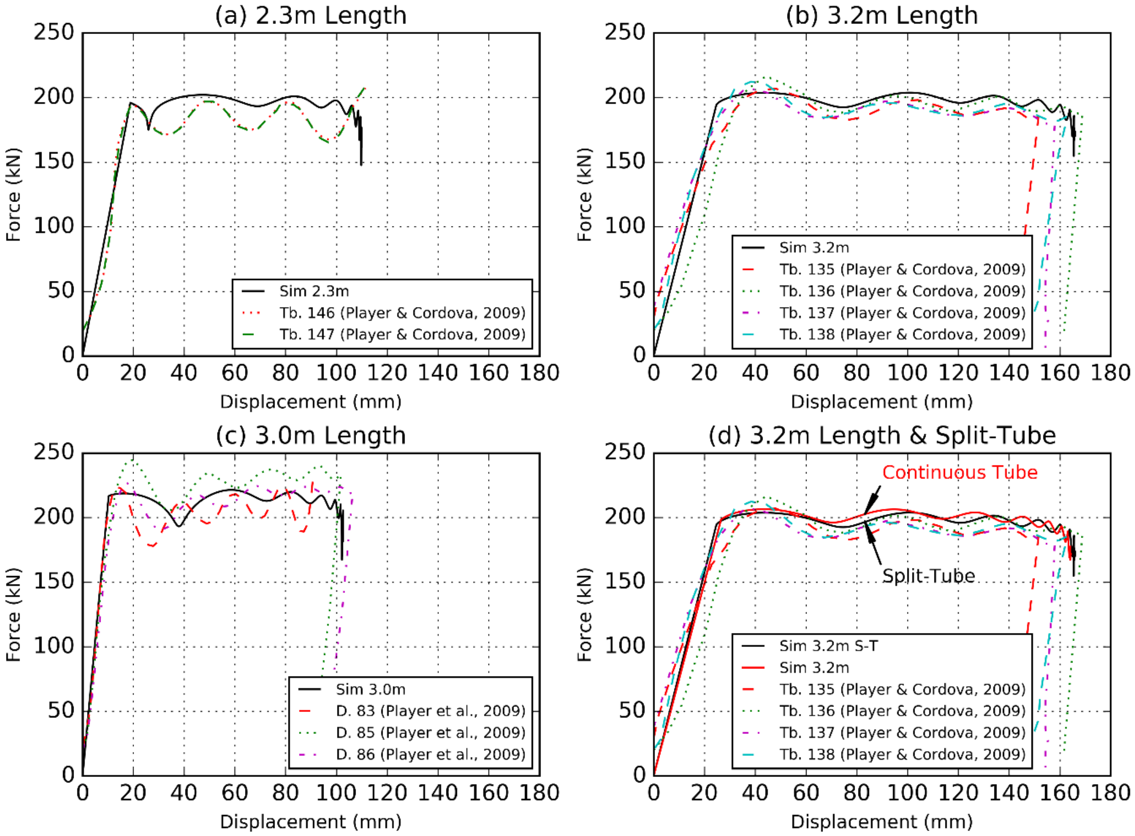

Figure 8 Model response comparison with test results. (a) 2.3 m rockbolt length. (b) 3.2 m rockbolt length. (c) 3.0 m rockbolt length. (d) Comparison between continuous tube and split-tube configurations for a 3.2 rockbolt length (Tests results after Player et al., 2009; Player and Cordova, 2009)

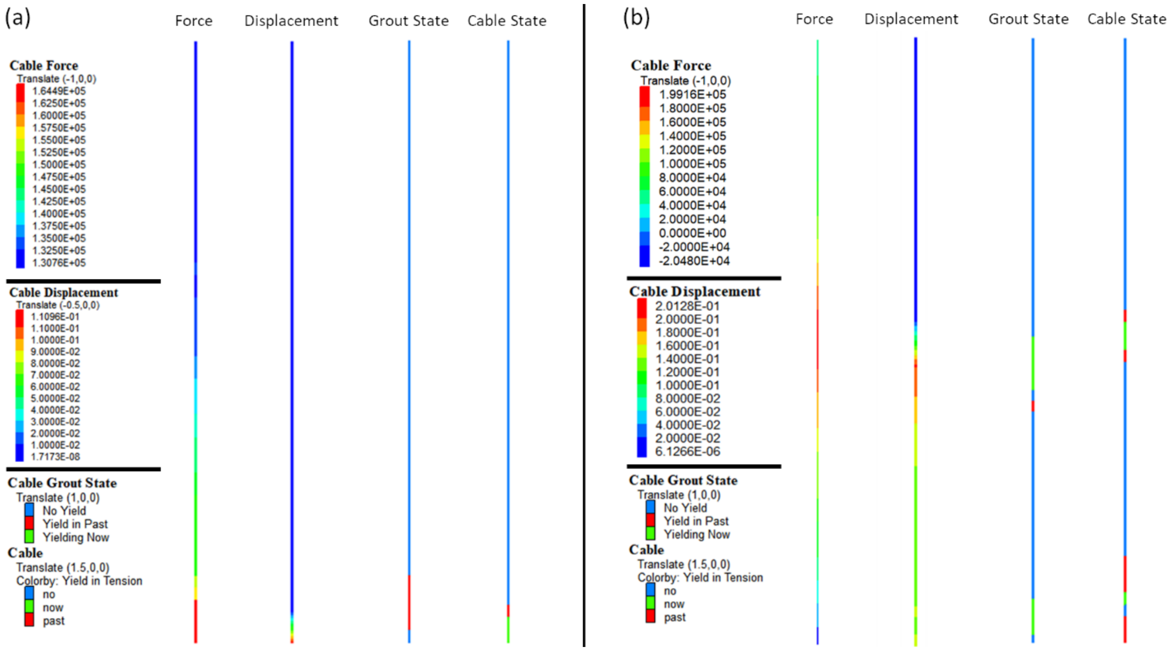

Figure 9 Example of final force (N), displacement (m), grout state and cable state profiles for a 3.2 m rockbolt length: (a) Continuous tube configuration. (b) Split-tube configuration

Table 1 **Calibrated parameters of the model for three different dynamic tests (Tests results after Player et al. 2009; Player and Cordova, 2009)**

Length	Bar diameter	Loading mass	Impact velocity	Borehole diameter	Radial stiffness	Dissipated energy	Rockbolt initial parameters		Grout initial parameters	
(m)	(mm)	(kg)	(m/s)	(mm)	(MPa/mm)	(kJ)	k (kN /mm)	c (Ns /mm)	k (kN /mm)	c (Ns /mm)
2.3	22	1964	6.7	45	1010	19.7	10.42	12.10	15.24	0.25
3.0	22	1964	7.6	45	1010	20.9	21.06	16.43	19.38	2.09
3.2	22	1964	7.9	45	1010	30.5	7.87	16.88	20.50	2.51

4.2 Parametric analysis

Considering the response of the calibrated model for a 3.2 m rockbolt length as a reference, a parametric analysis of the most incident parameters at the laboratory-scale dynamic tests is performed. Different values for the loading mass, the length, the diameter of the threadbar, and the water-cement ratio of the grout are considered. Figure 10a illustrates the change in the dynamic response of threadbar when the loading mass is modified for a rockbolt length and diameter of 3.2 m and 22 mm, respectively. Figure 10b shows the change in the dynamic response when the length of the threadbar is modified for a constant loading mass of 2 tonnes and a fixed rockbolt diameter of 22 mm.

The change in the dynamic response when the diameter of the threadbar is modified for a fixed rockbolt length of 2.3 m and a constant loading mass of 2 tonnes is illustrated in Figure 10c. Finally, Figure 10d shows the change in the dynamic response when the water-cement ratio of the grout is modified with a fixed rockbolt length of 3.2 m and a constant loading mass of 2 tonnes. Table 2 presents a summary of the parameters used in the parametric analysis for the simulations of the numerical model.

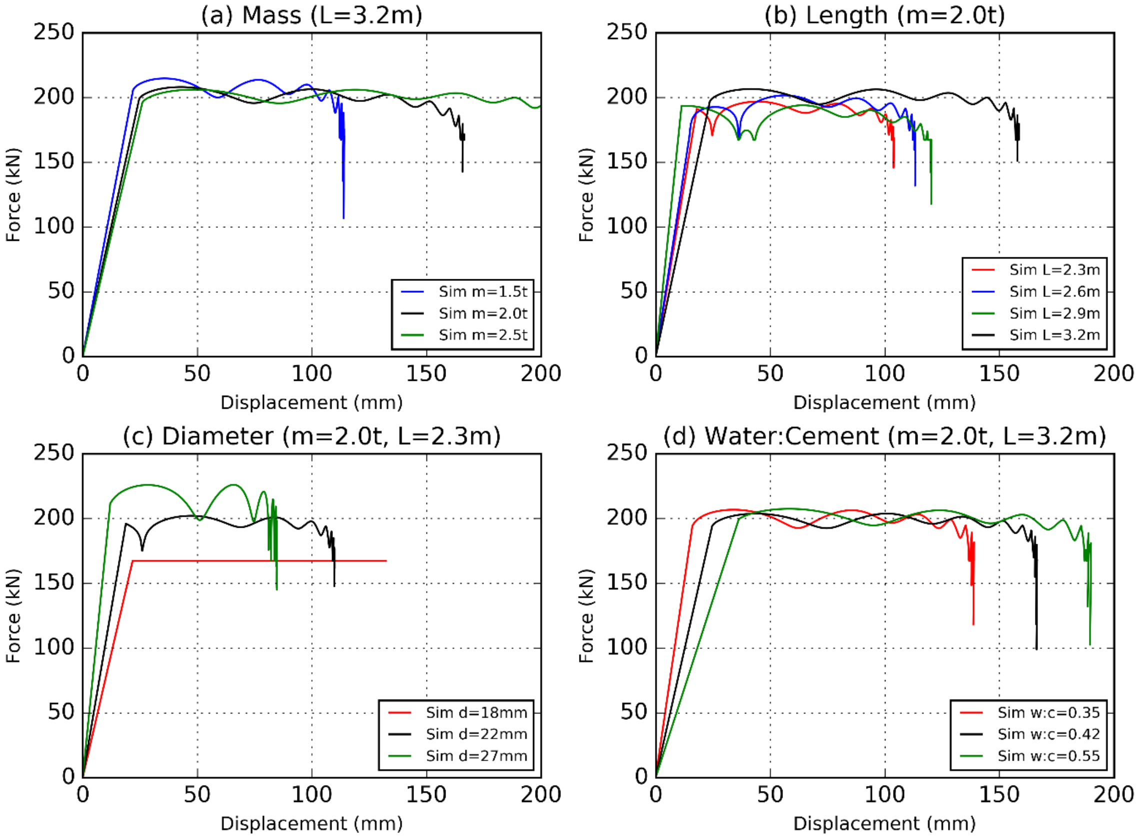

Figure 10 Parametric analysis results from the simulations of the calibrated numerical model. (a) Response to changes in the loading mass. (b) Response to changes in the rockbolt length. (c) Response to changes in the rockbolt diameter. (d) Response to changes in the water-cement ratio of the grout

Table 2 Parameters used for the simulations of the numerical model for the parametric analysis

Simulation ID	Length	Bar diameter	Loading mass	Water-Cement ratio	Dissipated energy	Maximum displacement
	(m)	(mm)	(kg)		(kJ)	(mm)
Sim m=1.5t	3.2	22	1500	0.42	21.3	114.1
Sim m=2.0t	3.2	22	1964	0.42	30.5	164.3
Sim m=2.5t	3.2	22	2500	0.42	39.9	212.3
Sim L=2.3m	2.3	22	1964	0.42	18.1	104.0
Sim L=2.6m	2.6	22	1964	0.42	20.3	113.3
Sim L=2.9m	2.9	22	1964	0.42	21.3	120.4
Sim L=3.2m	3.2	22	1964	0.42	29.4	158.5
Sim d=18mm	2.3	18	1964	0.42	30.7	199.8
Sim d=22mm	2.3	22	1964	0.42	19.7	109.9
Sim d=27mm	2.3	27	1964	0.42	26.7	130.3
Sim w:c=0.35	3.2	22	1964	0.35	26.1	138.9
Sim w:c=0.42	3.2	22	1964	0.42	30.6	164.4
Sim w:c=0.55	3.2	22	1964	0.55	34.3	190.0

4.3 Verification of the model

To verify the performance of the calibrated numerical model, an additional laboratory-scale dynamic test result for threadbar from an impact test facility is used. The result of this test was not considered during the calibration process and the rockbolt presents different diameter and steel grade. Figure 11 illustrates the comparison between the results of the calibrated numerical model and the additional laboratory-scale dynamic test. Table 3 shows the parameters considered in this additional dynamic test and in the simulation of the numerical model. As a reference, Table 3 also includes the parameters obtained from the calibration stage and the effect of the loading mass on the dynamic response of threadbar for the same configuration of the additional test.

Finally, the tendency between the dissipated energy and the maximum displacement induced on rockbolts during the numerical simulations and laboratory-scale tests is analysed. For the case of the numerical model simulations, the results considering different parameters are included in the analysis. For the laboratory-scale tests the results from both dynamic and static tests for threadbar and D-bolt are considered (Doucet and Voyzelle, 2012; Li and Doucet, 2012; Player and Cordova, 2009; Player et al., 2009; Villaescusa, 2012). Figure 12 presents the results of the analysis.

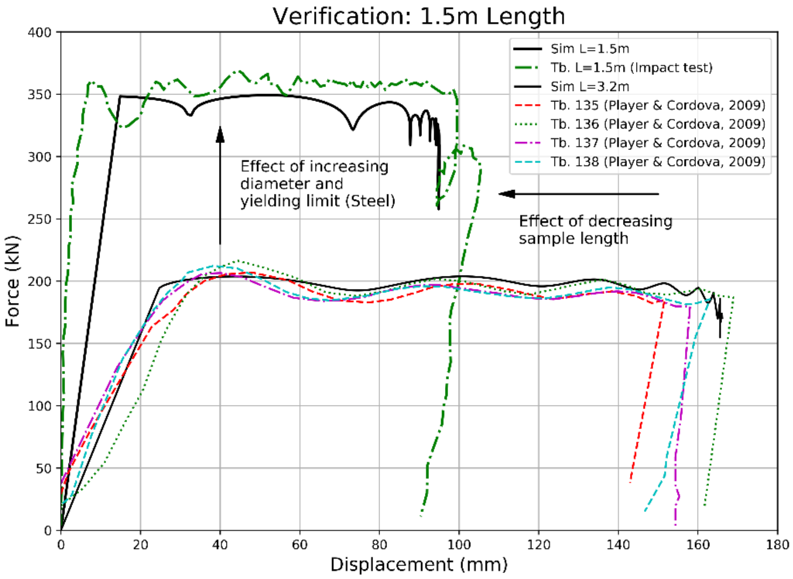

Figure 11 **Verification of the model performance with an additional test result from an impact test facility. The figure also includes the comparison between the model response with the tests results for 3.2 m length rockbolts**

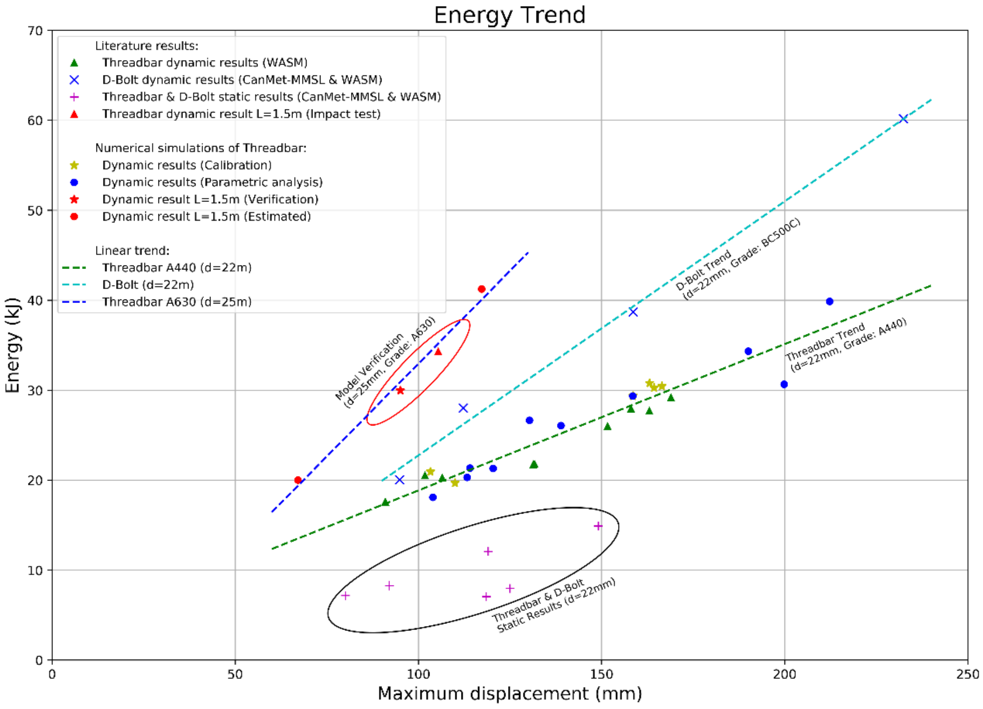

Figure 12 **Dissipated energy as a function of the maximum displacement obtained from numerical simulations and laboratory-scale tests results from the literature. The performance of threadbar and D-bolt are included in the analysis (Tests results from Doucet and Voyzelle, 2012; Li and Doucet, 2012; Player and Cordova, 2009; Player et al., 2009; Villaescusa, 2012)**

Table 3 Parameters considered for the simulations of the numerical model for the verification, calibration and quantification of the loading mass effect

Test / Simulation ID	Steel grade	Length (m)	Minimum yielding strength (MPa)	Ultimate strength (MPa)	Bar diameter (mm)	Loading mass (kg)	Water-Cement ratio	Dissipated energy (kJ)	Maximum displacement (mm)	Energy error	Displacement error	Stage
Tb. L=1.5m	A630	1.5	420	630	25	2897	0.42	34.3	105.4	12.5%	9.8%	Verification
Sim L=1.5m	A630	1.5	420	630	25	2897	0.42	30.0	95.0			
Tb. 136	A440	3.2	280	440	22	1964	0.42	29.8	168.9	2.3%	2.7%	Calibration
Sim L=3.2m	A440	3.2	280	440	22	1964	0.42	30.5	164.3			
E. Sim. L=1.5m	A630	1.5	420	630	25	2397	0.42	20.0	67.1	-	-	Estimated
E. Sim. L=1.5m	A630	1.5	420	630	25	3397	0.42	41.2	117.2			

5. Discussion

The comparison between the simulations of the numerical model and the laboratory-scale test results from the WASM facility for the dynamic response of threadbar presents a reasonable similarity. In this sense, the numerical model represents a feasible approach to simulate the dynamic response of threadbar under laboratory-scale conditions. The results are discussed in this section.

Based on the results of the numerical model (Figure 8 and Figure 10), the oscillatory profile observed at the yielding limit of the threadbar after the impact of the loading mass on the plate, corresponds directly to the velocity profile generated by the combined movement of the mass and the reinforcement element. This response is consistent with the estimated dynamic increase factor (Malvar and Crawford, 1998), that depends directly on the strain rate and therefore on the velocity profile. The fundamentals of this oscillatory behaviour during the yielding condition, can be explained by the hysteretic loading profile of the rockbolt when the dynamic plastic deformation zone is reached. This, is a result of the deformation of multiple segments at different intervals producing an overlapping response. Nevertheless, the understanding of the nature of this process needs further research to verify this possible description.

It is interesting to note, that the dynamic response in terms of the load-displacement curve is practically the same for both the continuous tube and the split-tube configurations (Figure 8d). This behaviour is related to the monitoring point defined in the model and the homogeneous properties of the segments which conform the cable element that represents the threadbar. Therefore, this response is expected and is concordant with the observations and results from the literature (Doucet and Voyzelle, 2012; Player and Cordova, 2009; Player et al., 2009, 2004) where the maximum deformation (and load) occurs through the discontinuity of the encapsulating tube. This behaviour is also confirmed by the load, displacement, rockbolt state and grout state profiles presented in Figure 9a and b for the continuous tube and split-tube configurations, respectively.

The parametric analysis presented in Figure 10, as a result of the simulations of the numerical model, illustrates the effect in the dynamic response of threadbar related to the main parameters that influence the setup of laboratory-scale dynamic tests. In this context, Figure 10a shows a proportional relationship between the displacement of the threadbar and the loading mass used in the dynamic tests. Figure 10b indicates a proportional trend between the displacement and the length of the threadbar. Figure 10c illustrates an inverse proportional relationship between the displacement and the diameter of the threadbar. Figure 10d shows an inverse proportional relationship between the displacement of the threadbar and the water-cement ratio of the grout.

It has to be noticed, that the initial stiffness of the reinforcement system, illustrated in Figure 10, responds with the same proportional tendency of the threadbar displacement. In general, all tendencies shown above are consistent with the expected behaviour of the reinforcement elements according to the studied parameters. This also verifies the response of the numerical model to the changes in the configuration of the laboratory-scale dynamic tests.

Based on the results illustrated in Figure 8 and Figure 10, it can be observed that the behaviour of the grout has a limited influence on the ultimate load capacity of the reinforcement element. The grout mainly influences the initial stiffness, the final displacement and the velocity profile during the loading process. Furthermore, the grout slightly improves the damping of the complete system.

By analyzing the isolated behaviour (state) of the grout, it can be observed, that the yielding condition depends directly on the value of the cohesive strength. At this point, the yielding condition is propagated partially or completely through the rockbolt given the cohesive strength value used in the numerical model. In some sections of the rockbolt the yielding condition is reached before the grout, independently of the encapsulating tube configuration. This generally agrees with the observations made from laboratory-scale results of dynamic tests for threadbar (Player and Cordova, 2009; Player et al. 2009) and it is consistent with the grout yielding zone around the discontinuities of the encapsulating tube (Figure 9a and b).

The proposed numerical model does not considers the friction angle of the grout (Equation 7) nor the numerical corrections proposed by Bin et al. (2012) to the cohesive strength and friction angle. Even without these considerations, the numerical model presents a response consistent with the experience observed from laboratory-scale tests under static and dynamic loading conditions. It has to be recognized, that the behaviour of the grout under dynamic loading conditions is a research area under development, and therefore, the parameters presented in this paper should be considered as a first approximation of the actual behaviour.

It is remarkable, that the simulation used to verify the performance of the numerical model (Figure 11) using the calibrated parameters presented in Table 3 (Tb. L=1.5m), presents a reasonable response compared to the measured displacement and dissipated energy. Figure 11 also illustrates the simulated dynamic response of threadbar to a decrease in the length of the rockbolt, an increase in the diameter of the rockbolt, and also to a change in the steel grade with a higher nominal yield stress.

It is important to note, that the model represents a loading condition similar to the CanMet-MMSL testing facility, while the tests results used to calibrate the model are from the WASM testing facility. As was noted in Section 2, the results of tests for threadbar from CanMet-MMSL are not readily available from the literature. The calibration of the model was accomplished with a specific number of tests available from the literature and tested at the WASM facility. Nevertheless, it is interesting to note that the verification of the model was evaluated with a test result from an impact test facility, presenting a reasonable performance.

Figure 12 illustrates a summary of all the simulated cases with the numerical model and the results of test from the literature for threadbar and D-bolt, in terms of the maximum displacement and the dissipated energy. A linear trend between the maximum displacement and the dissipated energy for both rockbolts is observed. In this case, each rockbolt shows an intrinsic linear trend that mainly depends on the steel grade or the diameter of the rockbolt. These results respond to the parametric analysis shown in Figure 10 and the verification shown in Figure 11 where a change in the length of the rockbolt, the loading mass of the test or the water-cement ratio does not increase the yielding limit of the rockbolt.

The diameter of the rockbolt or the steel grade modifies the yielding limit, and therefore, the dissipated energy and the maximum displacement of the reinforcement element.

The implication is that, when the steel grade of a rockbolt is changed preserving its geometry, the properties of the material determines the nominal yielding limit and the nominal ultimate strength. When the diameter of the rockbolt is changed preserving the material, the yielding load changes, modifying the response. These variations lead to a change in the slope of the linear trend between the maximum displacement and the dissipated energy, and helps to explain the behaviour of different reinforcement elements.

The results found from the simulations of the numerical model are consistent with the results from the literature (Doucet and Voyzelle, 2012; Li and Doucet, 2012; Player and Cordova, 2009; Player et al., 2009) and can be considered as a feasible approach to explain the dynamic behaviour of the threadbar. The modelling approach proposed in this paper can be easily extended to other reinforcement elements.

Finally, it should also be observed that the results shown by the CanMet-MMSL facility and the WASM facility for reinforcement elements other than the threadbar are similar in terms of the dynamic load-displacement curve within an acceptable range (Player et al. 2008; Villaescusa, 2012; Li and Doucet, 2012; Doucet and Voyzelle, 2012), considering that both testing facilities are based on different concepts in their operation. This finding is also consistent with the case presented for the verification of the numerical model.

The proposed modelling approach has demonstrated to have a satisfactory performance to simulate the dynamic response of threadbar under laboratory-scale conditions. The model is adaptable and can be continuously adjusted as necessary, and represents a feasible tool to improve the understanding of the dynamic behaviour of reinforcement elements.

6. Conclusions

In this paper, a numerical model to evaluate the dynamic response of threadbar under laboratory-scale conditions was developed and implemented into a finite difference software (FLAC^{3D}). The calibration of the model involved the analysis of both the continuous and the split configurations of the encapsulating tube. Then, a parametric analysis and the verification of the calibrated model were presented. Finally, a compilation and analysis of the results in terms of the relationship between dissipated energy and displacement was presented.

As a consequence from the simulations of the numerical model, the dynamic response of threadbar under laboratory-scale conditions using the continuous tube and the split tube configurations are very similar. This is related to the monitoring point that depends on the encapsulating tube configuration and the homogeneous properties of the materials assigned to the tested elements. The configuration of the encapsulating tube influences the distribution of displacement, force, rockbolt yielding state and grout yielding state along the reinforcement element. In this sense, the response is concentrated at the free edges (discontinuity) along the encapsulating tube.

The direct relationship between the propagation velocity of the reinforcement element, the dynamic increase of the yielding point, and the ultimate strength is appreciated through the numerical simulations of the model. These parameters, evidenced during the simulation time, have a distinctive influence on the limit and the oscillatory profile of the yielding condition in the reinforcement element and are consistent with the observations made by Malvar and Crawford (1998).

Grout plays a limited role in the ultimate load capacity of the reinforcement system. The main effects of grout are related to the initial stiffness, damping and of course ensure a proper anchorage of the rockbolt. Furthermore, through the simulations of the numerical model, it can be concluded that the constitutive model of the grout, available in the commercial software FLAC^{3D}, may not be the best representation of the actual behaviour. This was also illustrated by Bin et al. (2012) for static tests. Despite the possible variables and parameters that were not considered, the numerical results are consistent with the results of dynamic tests from the literature. Further research with emphasis on the behaviour of grout under dynamic loading conditions are required.

It is remarkable that the dissipated energy and the maximum displacement follows a linear trend. Based on the model results, this behaviour depends mainly on the diameter of the rockbolt and the specified steel grade, which modifies the slope of the linear trend. Results from previous research (Doucet and Gradnik, 2010; Doucet and Voyzelle, 2012; Li and Doucet, 2012; Player et al., 2009; Villaescusa et al., 2015) support this behaviour for different reinforcement elements. As a final conclusion, the results of the simulations from the numerical model represent a valuable tool to visually support, enhance and illustrate the dynamic behaviour of reinforcement elements under laboratory-scale tests. The modelling approach presented in this paper can be adapted to other reinforcement elements and testing configurations.

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CHAPTER 3: CONCLUSIONS

The main conclusions of the thesis carried out are shown below:

- A numerical modelling to evaluate the response of threadbar under a future new dynamic testing facility to be built in Chile was developed and implemented into a finite difference software (FLAC^{3D}). The development of the model involved the analysis of both the continuous configuration of the encapsulating tube and the split configuration of the encapsulating tube, in order to compare and calibrate the numerical model. Then, a parametric analysis and a verification of the model was taken into account. Finally, a summary analysis of the previous results in terms of energy and displacement was presented.
- As a consequence of the numerical model, the results between the continuous tube configuration and the split tube configuration are very similar. This is attributable to the monitoring point depending on the encapsulating tube configuration and the homogeneous properties of the materials that involve the elements to be tested. Despite the above, the configuration of the encapsulating tube influences the distribution of displacement, force, rockbolt yielding state and grout yielding state along the reinforcement element. In this sense, the distribution is concentrated in the free edges (discontinuity) along the encapsulating tube.
- The direct relationship between the propagation velocity of the reinforcement element, the dynamic increase of its yielding point, and its ultimate strength is appreciable through the modelling. These variables, appreciable during the simulation time, have a distinctive influence on the limit and the oscillatory profile of the yielding condition in the reinforcement element and are consistent with the observations from Malvar and Crawford (1998).
- Grout plays a secondary role in the overall strength of the system, mainly influencing the system's stiffness and damping at first. Furthermore, through the numerical modelling, it was shown that the constitutive model of the grout, intrinsically present in FLAC^{3D}, may not be the best representation of its behaviour, as was illustrated by Bin et al. (2012) for static tests. Despite the possible variables that were not taken into account, the numerical results are concordant with testing results from literature for dynamic tests. However, further study with a major analysis of this particular component is required, considering that research on grout in dynamic conditions related to reinforcement elements is an area still in development.
- It is remarkable that the energy dissipated and the maximum displacement for the threadbar follows a linear trend. Based on modelling results, this behaviour depends mainly on the diameter of the rockbolt or its steel grade, which modifies graphically the slope of its intrinsic linear trend between maximum displacement and energy dissipated. In this case, results from previous research (Doucet and Gradnik, 2010; Doucet and Voyzelle, 2012; Li and Doucet, 2012; Player et al., 2009; Villaescusa et al., 2015) support this behaviour for different reinforcement elements and also verify the hypothesis raised at the beginning of this thesis.
- In addition, the work performed indirectly indicates a good correlation between results from the CanMet-MMSL facility and the WASM facility for the same reinforcement when the diameter, the steel grade and the configuration of the test are equivalent. However, it is recommended further studies to verify this behaviour.
- Summarizing, numerical modelling results represent a valuable tool to visually support, enhance and illustrate the dynamic processes of reinforcement elements under laboratory-scale dynamic testing. In addition, the model presented in this paper can be re-calibrated and adapted to other reinforcement elements and testing configurations.

3.1. Future Work

A summary of the main topics to be developed in the future is illustrated below:

- A better analysis of the grout influence in the system is required, taken into account more variables that describes its behaviour as the yielding limit, the friction coefficient, the dilatancy, etc. To accomplish this, laboratory test under static and dynamic loads are required together with a model that best describes its behaviour.
- Verification of the possible influence of another parameters in the behaviour of the reinforcement elements that were not taken into account in the model illustrated. Also, the possible implementation of another numerical models that redefine the problem conceptualization, including interaction with another reinforcement elements, retaining elements or complete support.
- Establish an acceptability criterion from dynamic testing to in-situ implementation. The criteria based on deformation (displacement) and energy are the most accepted until now (Kaiser and Cai, 2013), nevertheless a generalized consensus is still being developed.

CHAPTER 4: BIBLIOGRAPHY

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