LABORATÓRIO NACIONAL
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COMATFAIL – TÉCNICAS AVANÇADAS PARA MODELAÇÃO NUMÉRICA DE PROCESSOS DE FRATURA MATERIAL. APLICAÇÕES PRÁTICAS E DESENVOLVIMENTO DE UM PROGRAMA DE ELEMENTOS FINITOS

Relatório de progresso do projeto do P2I/LNEC até ao final de 2017

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Autoria

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Resumo

Neste relatório apresenta-se, de forma sucinta, a descrição da atividade de investigação realizada no âmbito do projeto CoMatFail até ao final de 2017. É feita a apreciação da atividade desenvolvida, nomeadamente quanto ao grau de cumprimento do plano de trabalhos, bem como dos objetivos específicos e dos indicadores de desempenho propostos na ficha de projeto. São ainda referidas as aplicações dos resultados da investigação em trabalhos contratados ao LNEC e as candidaturas a financiamento externo desenvolvidas no âmbito do projeto.

Inclui-se em anexo a ficha do projeto atualizada, que contempla a revisão do plano de trabalhos.

Palavras-chave: CoMatFail / Fratura material / Modelação numérica / Barragens de betão / Controlo de segurança / Análise até à rotura

COMATFAIL - ADVANCED TECHNIQUES FOR COMPUTATIONAL MATERIAL FAILURE MODELING. PRACTICAL APPLICATIONS AND DEVELOPMENT OF A FINITE ELEMENT SOFTWARE

Progress report of the P2I/LNEC project by the end of 2017

Abstract

This report briefly presents a description of the research activities performed for the CoMatFail project up to the end of 2017. It is presented an appreciation of the developed activity, namely about the degree of agreement with the work plan timeline, and as well, with the task goals and performance indicators, that are proposed in the project sheet. In the final part, the report presents the practical applications of the project results in works contracted to LNEC and the applications to project grants.

Attached to the report, it is included the updated project sheet, which contains a revision of the work plan timeline.

Keywords: CoMatFail / Material failure / Numerical modeling / Concrete dams / Safety control / Failure analysis

Índice

Índice de quadros

1 | Introdução

O projeto de investigação CoMatFail teve início formal em 01/01/2016 e tem uma duração total prevista de 48 meses.

O projeto está integrado no Plano de Inovação e Investigação (P2I) do LNEC e tem enquadramento na matriz programática da Estratégia de Investigação e Inovação 2013-2020 (E2I), nomeadamente no eixo estruturante E1 (Património construído) e eixo transversal E4 (Risco e segurança), e nas temáticas T2 (Novas tecnologias) e T8 (Desenvolvimento de competências e transferência de conhecimentos).

A equipa de investigação do LNEC é formada pelos Bolseiros de Pós-Doutoramento Ivo Dias (Investigador Responsável), do DBB/NMMR, e Juan Mata do DBB/NO e pelo Investigador-Coordenador José Vieira de Lemos (Investigador Co-responsável), do DBB/NMMR. O projeto desenvolve-se em colaboração internacional com o Centro Internacional de Métodos Numéricos em Engenharia (CIMNE), de Barcelona, nomeadamente com o Professor Javier Oliver e com o Investigador Oriol Llorebas-Valls.

O projeto de investigação CoMatFail insere-se no campo da mecânica computacional, centrando-se, mais especificamente, nas análises estruturais até à rotura. O principal objetivo consiste em obter uma ferramenta numérica para a modelação de estruturas até à rotura, com suporte num programa de elementos finitos (CoMat) e diversas publicações, que possa apoiar os investigadores e engenheiros na avaliação e controlo de segurança de estruturas de betão.

2 | Atividade desenvolvida e divulgação de resultados

2.1 Descrição da atividade desenvolvida

Na Quadro 2.1 apresenta-se o plano de trabalhos proposto na ficha do projeto CoMatFail.

Quadro 2.1 – Plano de trabalhos proposto

				Data de início: 01-01-2016 *								
Tarefa	Designação da Tarefa	2015 1º Sem.	2015 2º Sem.	2016 1º Sem.	2016 2º Sem.	2017 1º Sem.	2017 2º Sem.	2018 1º Sem.	2018 2º Sem.	2019 1º Sem.	2019 2º Sem.	Total em meses
T1	Aplicação a barragens gravidade de betão											6
T2	Aplicação ao estudo da fratura dinâmica											15
T3	Extensão tridimensional											21
T4	Aplicações a barragens abóbada sob ações sísmicas											33
T5	Aplicação à deteção atempada de cenários de rotura de barragens de betão											12
T6	Otimização do software											18

*O projeto teve início formal no 1º semestre de 2016, no entanto considerou-se o ano de 2015 a cinzento para indicar que as tarefas já estavam, nessa altura, a ser desenvolvidas pelos membros da equipa do projeto.

A atividade desenvolvida até ao momento insere-se em 4 das tarefas que integram o plano de trabalhos do projeto:

- **T1- Aplicação a barragens gravidade de betão** – Foram realizadas aplicações numéricas ao modelo reduzido de uma barragem gravidade, proposto e testado experimentalmente por Carpinteri (carregado através de macacos hidráulicos até à rotura) e à barragem de Koyna, para a qual existiam resultados numéricos obtidos por outros autores, que permitiram a validação do método.

  Durante a realização desta tarefa a formulação de elementos finitos foi atualizada. O efeito do tamanho da barragem (*size effect*) implica que os fenómenos de fratura se processem de forma mais frágil do que em problemas de menor dimensão, para os quais a formulação tinha sido inicialmente validada. A consequência deste facto é que os efeitos não lineares se concentram num volume muito pequeno em relação ao tamanho da estrutura, o que implicaria, no âmbito do método inicialmente proposto, a utilização de malhas com elementos finitos de tamanho muito reduzido para poder melhorar as zonas com comportamento não linear que evoluem na frente da fissura (que são injetadas numericamente com os modos de deformação melhorados). Para contornar o problema foi proposta uma formulação mista estabilizada em deslocamentos e extensões aplicada a todo o domínio. No âmbito desta atividade foi publicado um artigo em revista internacional [1], no qual estes melhoramentos foram apresentados.

- **T2- Aplicação ao estudo da fratura dinâmica** – Foram realizadas diversas aplicações académicas para validação da metodologia aplicada ao estudo da propagação da fratura dinâmica. A principal dificuldade foi a simulação dos fenómenos de ramificação da fratura (*branching*), tendo sido realizados importantes melhoramentos nos algoritmos auxiliares para determinar os elementos finitos nos quais se processa essa ramificação. No âmbito desta atividade foi publicado um artigo em revista internacional [2] e foram apresentadas duas comunicações em congressos internacionais [3,4].
- **T3- Extensão tridimensional** - o programa de elementos finitos foi reformulado, com vista à sua generalização, para ser utilizado simultaneamente em 2D e 3D. Foram implementados elementos tetraédricos (de 4 nós) e cúbicos (de 8 nós).
  Os resultados iniciais, para os exemplos académicos mais simples, foram muito promissores, tendo sido já divulgados através de duas comunicações em conferências internacionais [5,6]. Verificaram-se para os casos mais complexos que envolvem fraturas curvas em modo misto, problemas de robustez e convergência numérica que foram, entretanto, mitigados. Está em fase de conclusão um artigo que será submetido a uma revista internacional da especialidade.
- **T6- Otimização do *software* -** O programa CoMat foi melhorado, nomeadamente na resolução do sistema de equações lineares (s*olver*), tendo-se para isso usado bibliotecas altamente eficientes, desenvolvidas pela Intel (MKL *Pardiso*), que tiram partido de programação em paralelo (OPENMP). Estes melhoramentos permitiram enfrentar o acréscimo de custo computacional inerentes às aplicações tridimensionais, sem aumentos significativos nos tempos de cálculo, que até ao momento não ultrapassaram 12 horas para os cálculos mais exigentes.

2.2 Apreciação da atividade desenvolvida e proposta de alteração

A atividade desenvolvida está, de forma genérica, de acordo com o inicialmente previsto, tendo sido alcançados os objetivos específicos das tarefas **T1** a **T3,** que estão descritos na ficha de projeto (Anexo). Desta forma a atividade de investigação a realizar no âmbito da tarefa **T4,** que dependia diretamente dos resultados das três tarefas predecessoras, poderá ser desenvolvida com normalidade.

Há apenas a referir que ocorreu algum atraso na conclusão da tarefa **T3** e no início da tarefa **T4**, pelo que o plano de trabalhos foi ajustado de forma a acomodar o atraso verificado, nomeadamente:

- Conclusão da tarefa **T3** durante o primeiro trimestre de 2018;
- Início da tarefa **T4** no primeiro trimestre de 2018 e conclusão no fim de 2019 (diminuindo a duração da tarefa de 33 para 24 meses);

- Início da tarefa **T5** no 2º semestre de 2018, mas mantendo a sua duração (12 meses).

No Quadro 2.2 apresenta-se o plano de trabalhos atualizado, o qual se inclui na ficha de projeto atualizada (no Anexo deste relatório).

Quadro 2.2 – Plano de trabalhos atualizado

				Data de início: 01-01-2016 *									
Tarefa	Designação da Tarefa	2015 1º Sem.	2015 2º Sem.	2016 1º Sem.	2016 2º Sem.	2017 1º Sem.	2017 2º Sem.	2018 1º Sem.	2018 2º Sem.	2019 1º Sem.	2019 2º Sem.	Total em meses
T1	Aplicação a barragens gravidade de betão											6
T2	Aplicação ao estudo da fratura dinâmica											15
T3	Extensão tridimensional											27
T4	Aplicações a barragens abóbada sob ações sísmicas											24
T5	Aplicação à deteção atempada de cenários de rotura de barragens de betão											12
T6	Otimização do software											18

2.3 Divulgação de resultados

A divulgação de resultados foi realizada através da apresentação de artigos em congresso e da publicação de artigos em revista. Foram apresentadas quatro comunicações em congressos e publicados dois artigos em revista, até ao final de 2017. Estas publicações são referenciadas na Secção 2.1, no âmbito da tarefa em que foram desenvolvidas.

Artigos publicados em revistas internacionais:

[1] Dias, I.F.; Oliver, J.; Lemos, J.V.; Lloberas-Valls, O., 2016 - **Modeling tensile crack propagation in concrete gravity dams via crack-path-field and strain injection techniques**. Engineering Fracture Mechanics, Volume 154, Pages 288-310, http://dx.doi.org/10.1016/j.engfracmech.2015.12.028

[2] Lloberas-Valls, O.; Huespe, A.E.; Olivera, J.; Dias, I.F., 2016a - **Strain injection techniques in dynamic fracture modeling**. Computer Methods in Applied Mechanics and Engineering. Volume 308, August 2016, Pages 499–534 http://dx.doi.org/10.1016/j.cma.2016.05.023

Comunicações em congressos internacionais:

[3] Lloberas-Valls, O., Huespe, A. E., Oliver, J.; Dias I. F., 2016 - **Crack path field and strain injection techniques in dynamic fracture simulations**. European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Crete Island, Greece p. 1-18

[4] Lloberas-Valls, O.; Oliver, J.; Huespe, A. E.; Dias I. F., 2017 - **Dynamic fracture simulations through strain injection techniques.** Fifth International Conference on Computational Modeling of Fracture and Failure of Materials and Structures – CFRAC, Nantes, France

[5] Dias, I. F., Oliver, J., Lloberas-Valls, O, 2016 - **Crack path field and strain injection techniques in 3D fracture modeling of quasi-brittle materials.** European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Crete Island, Greece

[6] Dias, I. F., Oliver, J., Lloberas-Valls, O., 2017 - **Modelação numérica da fratura em 3D. Técnicas de injeção de modos de deformação.** Congreso de Métodos Numéricos en Ingeniería -CMN Valencia, Espanha

3 | Indicadores de desempenho e afetação de recursos humanos

No Quadro 3.1 apresentam-se os indicadores de desempenho do projeto, designadamente o previsto e já realizado para o período de 2016 a 2017 e o total previsto na ficha de projeto. Foram até ao momento realizadas quatro comunicações em conferências internacionais e publicados dois artigos em revista internacional, mas deve referir-se que um terceiro está neste momento em fase de conclusão, prevendo-se que seja publicado durante 2018. Até ao final do projeto prevê-se que sejam ainda realizadas mais duas comunicações em congressos, duas publicações em revista internacional e uma em revista nacional e que seja elaborada uma tese de mestrado no âmbito do projeto, existindo, portanto, a expetativa de que os indicadores inicialmente previstos sejam cumpridos.

Relativamente ao *software* CoMat, que é o principal produto do projeto, deve referir-se que se encontra num grau de desenvolvimento compatível com a atual fase de progresso do projeto.

Quadro 3.1 – Indicadores de desempenho

Indicadores	Realizado / Previsto em 2016-2017	Total previsto no projeto
Artigos em revista internacional	2 / 3	5
Comunicações em congresso	4 / 4	6
Artigos em revista nacional	0 / 0	1
Teses de mestrado	0 / 0	1
Software CoMat	(em desenvolvimento)	1

No Quadro 3.2 apresentam-se os recursos humanos do LNEC afetados ao projeto, os meses de trabalho previstos e efetivamente dedicados no período de 2016 a 2017 e o total previsto na ficha de projeto, verificando-se que os valores previstos até ao final de 2017 são semelhantes, mas ligeiramente inferiores, aos efetivamente dedicados. De referir que o bolseiro de Pós-doutoramento Juan Mata ainda não iniciou a sua atividade no projeto, uma vez que a tarefa na qual vai colaborar tem início apenas em 2018.

Quadro 3.2 – Afetação de recursos humanos

Equipa do LNEC	Categoria	Meses de trabalho	
		Dedicado / Previsto em 2016-2017	Total previsto no projeto
Ivo Dias	Bolseiro de Pós-doutoramento	9,0 / 10,8	21,6
José Vieira de Lemos	Investigador-Coordenador	0,6 / 1,2	2,4
Juan Mata	Bolseiro de Pós-doutoramento	0 / 0	2,4

Face ao exposto, e tendo em conta que o tempo dedicado ao projeto foi ligeiramente inferior ao previsto, considera-se que é possível concretizar o plano de trabalhos atualizado, no qual a tarefa T4 passou de 33 para 24 meses de duração, recuperando, para o período de 2018 a 2019, parte do tempo que não foi utilizado no período de 2016 a 2017, não sendo, portanto, necessários ajustamentos aos valores globais da efetuação de recursos humanos ao projeto.

4 | Financiamento externo

4.1 Candidaturas a projetos financiados

A atividade de investigação realizada pela equipa do LNEC no âmbito do projeto CoMatFail é atualmente financiada, na sua totalidade, por fundos do próprio LNEC. No sentindo de captar financiamento externo para o projeto, foram promovidas duas candidaturas a concursos, uma das quais a uma bolsa de pós-doutoramento, com a qual se pretendia financiar a atividade do investigador responsável do projeto (Bolseiro de Pós-Doutoramento Ivo Dias), e uma segunda a um projeto de investigação, que poderia vir a financiar os bolseiros de pós-doutoramento envolvidos, ou outros bolseiros a contratar, bem como despesas com a aquisição de equipamentos científicos e missões.

A candidatura à bolsa de pós-doutoramento foi submetida à FCT em julho de 2016, com o título "Técnicas avançadas para modelação numérica de processos de fratura material", não tendo sido selecionada para financiamento. Participaram nesta candidatura como orientadores o Investigador-Coordenador José Vieira de Lemos e o Professor Javier Oliver.

A segunda candidatura, que tem acrónimo e título idênticos ao do atual projeto de investigação, foi submetida no âmbito do concurso para projetos de investigação científica e desenvolvimento tecnológico em todos os domínios científicos, financiado por Fundos Europeus Estruturais e de Investimento e por fundos nacionais, através da FCT. A candidatura, submetida em maio de 2017, foi elaborada em colaboração com o Centro Internacional de Métodos Numéricos em Engenharia (CIMNE), tendo sido solicitado um orçamento total para o LNEC de €239.930,81. Neste momento os resultados desta candidatura ainda não são conhecidos.

4.2 Aplicações a trabalhos de contrato

O programa de elementos finitos CoMat, que está a ser desenvolvido no âmbito do presente projeto, foi usado na avaliação da capacidade estrutural de cúpulas de blocos cerâmicos, que foi solicitada pela empresa ABRIGADA - Companhia Nacional de Refractários, S.A. ao LNEC. Estas cúpulas têm uma estrutura aneliforme, variando desde os dois anéis, para vencer vãos de 2060 mm, até um máximo de nove anéis, para vãos até 9472 mm. De referir que a avaliação de segurança se apoiou em oito modelos numéricos tridimensionais de elementos finitos (tendo sido utilizados elementos tetraédricos de 4 pontos nodais), correspondentes às cúpulas de 2 a 9 anéis.

De referir que os bons resultados obtidos em termos de eficiência computacional com a implementação das rotinas de resolução do sistema de equações lineares (MKL Pardiso) no programa CoMat, conduziram a que as mesmas fossem também implementadas no programa FLUDAN (também em melhoramento no LNEC no âmbito do projeto DamSwelling). O programa

FLUDAN foi, entretanto, utilizado em vários estudos relevantes aplicados a barragens de betão, nomeadamente:

- Atualização do estudo de análise e interpretação do comportamento observado da barragem de Cahora Bassa, incluindo as estruturas salientes do descarregador de meio;
- Análise do comportamento observado durante o primeiro enchimento e o primeiro período de exploração da barragem de Bouçoais-Sonim;
- Análise do comportamento durante o primeiro enchimento da albufeira da barragem do Baixo Sabor.

5 | Considerações finais

A execução do projeto CoMatFail, descrita de forma sucinta neste relatório, tem decorrido genericamente de acordo com o proposto na ficha de projeto, tanto ao nível da execução das várias tarefas do plano de trabalhos como no grau de cumprimento dos objetivos e realização dos indicadores. Há apenas a referir algum atraso na finalização da tarefa **T3- Extensão tridimensional** e no início da tarefa **T4- Aplicações a barragens abóbada sob ações sísmicas**, tendo a ficha de projeto sido atualizada de forma a incluir este ajuste no plano de trabalhos. Sendo o atraso relativamente reduzido, não foram feitas alterações à afetação de recursos humanos nem aos objetivos e indicadores inicialmente propostos.

Lisboa, LNEC, fevereiro de 2018

VISTOS

O Chefe do Núcleo de Observação

António Tavares de Castro

O Chefe do Núcleo de Modelação e Mecânica das Rochas

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Bolseiro de Pós-Doutoramento

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Investigador-Coordenador

Juan Mata

Bolseiro de Pós-Doutoramento

ANEXO
Ficha do projeto atualizada

FICHA DE PROJETO DE I&D&I (versão2)
2013-2020

1 - Dados Gerais

1.1 Identificação do projeto

Designação	Técnicas avançadas para modelação numérica de processos de fratura material. Aplicações práticas e desenvolvimento de um programa de elementos finitos Em inglês: Advanced techniques for computational material failure modeling. Practical applications and development of a finite element software
Acrónimo	CoMatFail
Unidade Departamental proponente	DBB
Setor	NMMR
Investigador Responsável	Ivo Miguel Dias
Duração (meses)	48
Data de início (ano-mês-dia)	01/01/2016

1.2 Inserção na matriz programática da E2I (indicar par(es) (Eixo programático, Temática prioritária))

Par principal (obrigatório)	E1, T2
Par secundário (opcional)	E4, T8

1.3 Entidades intervenientes

Entidade coordenadora	Laboratório Nacional de Engenharia Civil (LNEC)
Parceiros internos	DBB/NO
Parceiros externos	International Center for Numerical Methods in Engineering (CIMNE)
Entidade externa interessada	Instituto Superior Técnico (IST)
Financiamento externo (S/N)	N

1.4 Resumo

(max. 300 palavras)

O presente projeto de investigação insere-se no campo da mecânica computacional, centrando-se, mais especificamente, nas análises estruturais até à rotura.

As estruturas são projetadas para terem, ao longo da sua vida útil, um comportamento elástico linear. No entanto, processos de deterioração de materiais ou cenários não previstos podem, eventualmente, dar origem a colapsos estruturais. Por essa razão, o processo de controlo de segurança de estruturas cujas consequências, em caso de rotura, sejam potencialmente catastróficas, como é o caso das grandes barragens, assume particular relevância. A avaliação da margens de segurança estrutural depende, em grande medida, da disponibilidade de modelos representativos dos processos de rotura.

Apesar dos grandes esforços de investigação que têm vindo a ser feitos desde a década de 1960, a modelação até à rotura de estruturas e materiais é ainda um problema em aberto. Métodos numéricos implementados com base no método dos elementos finitos e desenvolvidos durante as décadas de 1970-1980 [1, 2] são, devido à sua simplicidade e disponibilidade em programas comerciais, muito usados na prática. No entanto, é conhecido que os resultados obtidos com estes métodos são muito dependentes da malha de elementos finitos, o que é crítico uma vez que diferentes malhas podem fornecer diferentes resultados, tanto em termos da trajetória das fendas como em termos da capacidade resistente última da estrutura (que não é do lado da segurança).

Este projeto de investigação tem como ponto de partida as novas técnicas desenvolvidas e propostas recentemente, designadamente as "crack-path field and strain injection techniques", especificamente desenvolvidas para ultrapassar as desvantagens dos métodos clássicos. Apesar do grande potencial da metodologia, até ao momento, esta foi implementada apenas em 2D. Desta forma, o principal objetivo deste projeto de investigação é, através de um conjunto de tarefas, desenvolver a metodologia de forma a que novos campos de aplicação possam ser consderados. As tarefas dedicas às aplicações práticas foram selecionadas de forma a responder a necessidades atuais de engenharia em termos de modelação numérica.

No final deste projeto de investigação pretende-se obter uma metodologia de carácter geral para a modelação de estruturas até à rotura, com suporte num programa de elementos finitos e diversas publicações.

Em inglês:

The present research project is inserted in the field of computational mechanics, more specifically in the computational failure analysis field.

Civil engineering structures are designed for behaving in linear elastic regime. However, ageing or unexpected scenarios can eventually trigger structural collapses. By this reason, the safety control process of structures, which failure can potentially cause possible catastrophic scenarios, like large dams, is of fundamental importance. The accurate assessment of the safety margins crucially relies in the availability of representative models of material failure.

Although a lot of research effort have been made since 1960s, numerical failure modeling still remains an opening and challenging problem. Numerical methods, implemented in the framework of the finite element method, developed in the 1970s – 1980s, ([1, 2]), are due to their simplicity and availability in commercial codes, very used in practice. However, it is known that these methods are strongly mesh dependent. This issue is critical for the reason that different meshes can deliver different results in terms of either, the crack trajectories or the ultimate loading carrying capacity, which is not in the safety side.

The departure points for this research project are the recently developed crack-path-field and strain-injection techniques [3-6], closely related to the Continuum Strong Discontinuity Approach [7, 8], that were specifically devised for overcoming the flaws of the classical methods. Despite the great potential of this new methodology, so far, it was only implemented in 2D. Therefore, the main goal of this research project is to further develop and extend the methodology (*e.g.* include inertial effects, 3D, *etc*.) through a set of research tasks such that new relevant fields of application can be open. The tasks devoted to practical applications were selected for responding to actual practical engineering needs in terms of failure modeling.

At the end of this research project, we intend to obtain a general methodology for modeling material failure (supported by a finite element code and several publications) that can help engineers in the design and safety control of special important structures.

2 - Fundamentação

(síntese do *estado da arte, identificação de problemas por resolver, motivações internas e/ou externas)*

During the last decades, a large number of proposals of models for propagating material failure have been done by the computational mechanics community. Here, two different classification criteria are chosen:

(1) The first criterion refers to the manner that the de-cohesion process at the crack or slip-line interface is modeled:

● In the discrete approach the mechanical behavior at the interface is described in terms of a traction-separation law [1].

● In the *continuum approach,* the mechanical behavior at the interface is described by a standard stress-strain constitutive model. The difficult point here is to relate the "interface strain" with the physically meaningful displacement jump. The *Continuum Strong Discontinuity Approach* [7] shows that any constitutive model, when applied to a strain field described by a regularized strong discontinuity, induces an equivalent (projected) traction-separation law at the discontinuity interface. This provides a clear link between continuum and discrete approaches [8].

It can be argued in favor of the continuum approach that the same constitutive model can be used for the continuous domain and the discontinuity interface, this leading to advantages as a less invasive implementation in commercial finite element codes.
(2) The second criterion is the one in terms of the selected numerical approach for capturing the crack/slip-line (the displacement jump):

● The strain-localization-based methods use continuum (stress-strain) constitutive models, equipped with softening, such that strains localize in narrow bands that under ideal conditions encompass just one finite element. The fact that this phenomena can be observed by just introducing strain softening in a constitutive model, made this approach early used and investigated [2]. These are the more intuitive, easier and conceptually simpler models but the main flaw is the spurious dependence on the mesh alignment (mesh-bias dependence and stress-locking effects).
● In the *supra-element-band methods*, a regularized displacement jump is captured by a band of finite elements encompassing *several elements* across its (characteristic length) bandwidth. This class of models include the *material-regularization-based approaches* (non-local, gradient or Cosserat models [9, 10]) and the more recent *phase field models* for fracture [11]. In general, good results are obtained, however, the fact that the size of the finite element is smaller than the, tiny, characteristic length implies that a huge number of elements is required, this leading to huge computational costs.

● In the *intra-elemental methods*, the discontinuity interface settles *inside* the finite element, thus, no restrictions in the size of the finite elements exist and coarse meshes can be used. Besides, also mesh-bias spurious dependences are overcome. In these methods the *finite elements are enriched with additional discontinuous displacement modes* and are termed E-FEM [7] or X-FEM [12], if the support of the additional modes is elemental or nodal, respectively. The performances of both methods are similar [13], but some benefits for E-FEM can be obtained due to the elemental support of the enriching modes that can be condensed out leading to lower computational cost.

However, in both methods, robustness depends on the precise determination of the position of the discontinuity, that is classically done by crack-tracking algorithms that are cumbersome to implement, have a code-invasive character and may seriously affect the robustness of the method [14]. These drawbacks seem to introduce some difficulties in modeling real-life problems and in commercial codes incorporation.

In very recent research developed during the last five years [3-6] (included in the Ph.D. studies of Ivo Dias), new numerical technics (crack-path-field and the strain-injection technics) devised for modeling propagating material failure were proposed. This new methodology consists on the combination of two new numerical technics. The first one is termed crack-path-field technique and is conceived for the identification of the path of those cracks, or slip-lines, represented by strain-localization based solutions of the material failure problem. The second one is termed strain-injection, and consists of a procedure for inserting, in those elements that are going to capture the cracks, enhanced strain modes (constant and discontinuous) such that performance of the finite elements for modeling cracks/shear bands can be effectively improved, allowing a proper modeling of the entire failure process, from its beginning, by means of strain concentration in narrow bands, until the formation of a real discontinuity in the displacement field.

The new methodology was conceived in order to maintain the classical advantages of the "intra-elemental" methods for capturing complex propagating displacement discontinuities in coarse meshes, as E-FEM or X-FEM methods, without resorting to global code invasive tracking algorithms. Instead, due to the elemental local character of the crack-path field technique, the method can be straightforwardly implemented in a standard non-linear finite element code at the cost of some modification to affect, essentially, the "element level".

In the site http://www.cimne.com/compdesmat/vpage/1/0/Downloads, a monograph describing the new method [4], the finite element code used for the simulations and the corresponding user manual are available for download.

3 - Objectivos

(indicar para além dos objetivos científicos do projeto, os objetivos do investigador responsável e das entidades envolvidas)

The main goal of this research project is to contribute for the developing and consolidation of the newly developed numerical techniques (crack-path-field and the strain-injection technics), such that the strong potential of the methodology, supported in its benefits and numerical advantages (generality, robustness, mesh independence, conceptual simplicity, low computational cost and the non-evasive character of implementation in a general non-linear finite element code), can be transformed in an effective tool for modeling material failure that can help engineers in the design and safety control of special important structures.

For reaching this objective, the finite element software for COmputational MATerial FAILure (CoMatFail) analysis plays a fundamental role. Actually, CoMatFail is an academic software, developed at CIMNE during the PhD thesis of Ivo Dias, in which the strain injection techniques had been implemented. The goal here is, throughout the researching tasks, to further develop the academic program, such that, at the end of this research project, it can be distributed as a useful tool for being used by researchers and engineers in failure analysis modeling and in the safety assessment of concrete dams.

The research work will be sub-divided in several stages with different specific objectives. One of them is the extension of the methodology (so far implemented only for “quasi-static” 2D analysis) to 3D, which opens its application field to general structures. Besides, for a detailed simulation of structures loaded by seismic actions, the inertial effects cannot be discarded. Therefore, an extension to account of these effects will be developed, such that fast propagating dynamic fracture can be studied. These developments allow the detailed failure analysis of real-life structures loaded by seismic actions. Large concrete dams are, due to the high risk associated to collapse scenarios, a very interesting application field that will be investigated in depth.

The advantages and competiveness of the methodology is expected to be shown by a set of publications in specialized international journals (in diverse fields of applications) and by papers in international conferences.

4 - Contribuições inovadoras

(indicar as contribuições para o reforço dos conhecimentos, das competências e/ou dos recursos experimentais do LNEC)

Several major innovative contributions are expected to be provided during the research tasks:

(1) It will be the first time that the recently proposed crack-path-field and strain injection techniques will be used for modeling crack propagation in real structures such as concrete dams. In previous work [1], when the techniques were first proposed, they were only applied to academic benchmarks, while in very recent research [6] some practical applications to concrete gravity dams began to be explored.

(2) The extension of the methodology, so far implemented only for “quasi-static” 2D analysis, will open the application field of the new techniques to general structures under static or dynamic conditions. The team members think that the new numerical techniques, supported in its interesting properties and advantages, can be an important tool for improving the actual modeling capabilities of large concrete dams under severe seismic loads, allowing a better description of the failure mechanisms and enhancing the previsions of the dam safety margins.

(3) It is expect to contribute for the early detection of failure scenarios by using the strain injections techniques for computing information about the potential dam failure mechanisms, and then integrating this information in the management systems for real-time control and decision. The early detection of failure scenarios will allow the implementation of automatic emergence actions for mitigating the catastrophic consequences associated to an eventual sudden flood wave.

(4) Thesoftware CoMatFail will be developed and maintained updated.

5 - Metodologia

(descrição da abordagem e dos métodos teóricos e/ou experimentais a utilizar)

1.1 General aspects

The departure points for this research project are the recently developed crack-path-field and strain-injection techniques devised for modeling propagating material (that were briefly described in section 1 of his research project). Due to the specific benefits and properties of the new techniques, the authors think that the methodology is particularly appropriated for being used in practice. These properties address directly the actual main issues of material failure modeling:

(1) Numerical cost – This is a very important question since results should be obtained in a reasonable and affordable amount of time. In the strain injection techniques the crack is captured inside the finite element, which means that coarse meshes can be used when compared with the finer meshes required by other methodologies (nonlocal [9, 10], phase field [11], etc.) that use several elements across the band for modeling the crack.

(2) Robustness – Lack of convergence of the iterative procedure is one of the main difficulties which can seriously affect the robustness of the numerical model. This question is overcome by using an implicit–explicit integration [15] of the non-linear constitutive equation associated to arch-length techniques.

(3) Noninvasive numerical implementation – The strain-injection technique, in combination with the crack-path-field technique, avoids the code invasive global crack tracking algorithms, usually used in association with other intra-elemental approaches (E-FEM [7] or X-FEM [12]), with no apparent cost in terms of robustness. This issue has a strong advantage, since the implementation tasks in a non-linear finite element code, affects, essentially, the element level.

(4) Generality – The methodology implementation affects exclusively the finite element formulation, this meaning that, in principle, any continuum constitutive model equipped with strain softening can be used, with no other limitation than their physical appropriateness for the considered material to be modeled (concrete, reinforced concrete, steel, soils, etc.).

(5) Accuracy and mesh independence – the strain injection techniques allows, by inserting some enhanced strain modes in those elements that are going to capture the cracks, a very detailed and accurate modeling of the entire failure process, from its beginning, by means of strain concentration in narrow bands, until the formation of a real discontinuity in the displacement field. The accuracy of the obtained results is independent of the finite element mesh, being this one of the most important advantages of the method in front of other, simpler approaches (e.g. smeared approach, damage models, etc.).

So far, the mechanical ingredients of the approach have been simplified in the next aspects: 1) the kinematical description of the motion was simplified to infinitesimal strains, 2) the dimensions of the problem were reduced to the 2D cases, 3) dynamic effects have been neglected, and 4) thermal effects have been discarded. The specific objectives of this research project include the extension of this method in order to account for some of those aspects (typically 3D analysis and inertial effects) that will open relevant areas of practical applications.

The research work proposed in this project will be sub-divided in 6 tasks with different specific objectives:

- T1– Application to failure analysis of concrete gravity dams
- T2– Extension to fast dynamic crack propagation
- T3– Extension to 3D
- T4– Application to 3D seismic failure analyses of concrete dams
- T5– Application to early detection of failure scenarios of concrete dams
- T6– Software integration & optimization

Some of the tasks are developing tasks (2 and 3), devoted to extend the methodology to account the aforementioned simplifications adopted when the methodology was first presented. The extension to 3D (task 2) will open widely the application field. Besides, for a detailed simulation of structures loaded by seismic actions, the inertial effects cannot be discarded. Therefore, an extension to account of these effects will be developed, in task 3, such that fast propagating dynamic fracture can be studied. These developments will allow developing an application task devoted to the 3D failure analysis of dams, loaded by seismic actions (task 4).

Others tasks (tasks 1, 4 and 5) are devoted to applications of the methodology to real structures allowing, on the one hand, to detect and overcome eventual limitations that come up in practice, and, on the other hand, to prove that the methodology is ready for being used in practice by engineers, with advantages relatively to alternative methodologies. Moreover, the application field of tasks 4 and 5 are selected to be investigated for responding to actual practical engineering needs in terms of failure modeling. The five first tasks proposed in this project have therefore important specific goals.

Relatively to task 6, the nature of the task is distinct relatively to the previous ones and corresponds to the materialization of the overall goal of the project in a practical numerical tool, the CoMatFail software, that can be a useful tool for supporting researchers and engineers in failure analysis modeling and in the safety assessment of concrete dams.

Notice that the first research tasks (T1, T2 and T3) are part of the recent and ongoing research of some team members, being these tasks at different degrees of development. For giving a panorama of the actual progress of each task, the research performed in 2015 was included in the timeline of the project.

Even if the research tasks of this project are developed in the framework of civil engineering, with strong emphasis in the analysis of concrete dams, we would like to strongly remark that the application field of the new numerical technics is completely general, and can have potential impact in other disciplines, like mechanical engineering (for the design of automobiles, ships, planes and respective components and accessories), material designing, biomechanics, etc..

To successfully accomplish each of the proposed tasks (1-5), the next procedure consisting on the subdivision of each task in four sub-tasks will be followed:

- State of Art – At the beginning of each stage a specific state of art study will be performed in order to be aware of the classical but also the most recent advances in the corresponding specific field. In this sub-task the numerical examples for validation will be selected. These examples are to be selected depending on the amount of information available in the literature for comparison (either experimental or numerical results). Additionally, interesting real-life structures will also be selected to be studied, once the validation of the method is performed.

- Research and Implementation – The goal of this stage is the developing and implementation in the finite element code, the necessary numerical mathematical ingredients to extend the methodology to the new field of application. Depending on the specific stage being developed this sub-stage can be more or less time demanding.

- Validation and Simulations – Once the research and implementation stage is concluded, to validate the applicability of the method, numerical representative simulations of a wide range of benchmarks or specific interesting real-life engineering structures will be performed. The obtained numerical results will be compared with results obtained with alternative numerical approaches available in international journals or with experimentally observed results.

- Publication and Communications – At the end of each research stage, the achieved theoretical developments and the corresponding obtained numerical results are to be published in an international journal of the subject field. Furthermore, the approach will be also disseminated through communications in international conferences and by updating the finite element code.

T1 – Application to failure analysis of concrete gravity dams

Nowadays, structural safety of large dams remains a great concern due to the high potential risk associated to the collapse of this kind of structures. A dam failure, followed by a sudden flood wave, can result in large life losses and in strong environmental and economic impacts as it was reported for several catastrophic failure cases [16]. Historically, the main causes of significant dam failures are related to foundation defects (erosion, sliding on its rock foundation, *etc*.) [17]. Structural failures, when not directly caused by foundation weakness movements, are less frequent but its importance should not be minimized in the design neither in the safety control of the dam.

The specific goal of this task is to use the crack-path field and strain-injection technics in failure analysis of gravity concrete dams (in 2D and quasi-static regime) for modeling crack propagation through the dam body, obtaining mesh independent robust results in an affordable period of time. This task does not require, in principle, large additional developments at the level of the numerical formulation and its implementation, but instead, has the objective to verify/show the potential of the methodology for being used in practice, by carrying out a conclusive set of numerical simulations of real-life existing structures.

We remark that spurious mesh dependence effects can lead to unrealistic collapse mechanisms and/or to an overestimation of the ultimate loading carrying capacity, which is against to the safety. This dependence is critical since engineers cannot be strongly confident in the representativeness of the numerically computed failure mechanisms, which imposes, in the other hand, limitations in the safety control process of the structures, since the actual structural safety factor cannot be realistically estimated.

Some results obtained in undergoing research of the team members [6, 18] for the extensively studied Koyna dam, in India, and the concrete dam scale models (of a 96-m-high gravity dam) tested by Carpintieri [19], are strongly promising in terms of the applicability of the methodology to concrete dams. The comparative analysis of these results with those obtained by other authors, by using alternatives methods, allows point out the advantages of the methodology in terms of robustness, computational cost and mesh independence.

Members of the research team in this task:

Ivo Dias and José Vieira Lemos

T2 – Extension to fast dynamic crack propagation

Fracture phenomena in structural materials are strongly influenced by the dynamic character of the loading conditions. Experimental evidence shows that the loading rate has a clear effect on the strength, stiffness and ductility of the material [20]. At high loading rates, inertia forces play a substantial role in the overall resistance and in the propagation speed of the crack tip. In this scenario, failure modes change from mode I to mixed mode and unstable crack propagation such as curving and branching is observed when a critical crack velocity is exceeded [21]. Modeling this complex phenomenon is a current hot research topic.

The intra-elemental methods, E-FEM and X-FEM, are proven to be efficient methodologies to tackle fracture phenomena at a low computational cost without compromising robustness and objectivity of the algorithms. Nevertheless, is this methodology the position and orientation of the displacement discontinuity is obtained through the solution of a parallel algorithm, usually referred as crack-tracking algorithms. These tracking algorithms (also termed zero-level-set methods in the X-FEM terminology) are cumbersome to implement, have a code-invasive character and may seriously affect the robustness of the method when increasing complex crack patters are intended to be modeled, as is the case of those that appear for high loading rates.

When developing the strain injection techniques the authors were aware of the limitations and inconvenient of global-based crack tracking algorithms, especially when applied to solve fast dynamic crack propagation, and for that reason a new local-based approach, termed as the crack-path field technique, was proposed. This technique, used at the end of each time step (staggered scheme), was conceived for the identification of the spatial position of a propagating localization field, based in information coming, uniquely, from the localization field itself. The updating of the crack-path field at end of each time step, and the incremental character of the injection techniques (allowing a smooth evolution of the injection domains), give flexibility and stability to the methodology, which is a key issue for modeling high rating varying loading problems.

On the other hand, some difficulties on the crack-path field techniques in order to deal with the region where the branching phenomena takes place can be anticipated. In fact, at the onset of crack branching, primary and secondary branches might be represented by different crack path sets which cannot intersect each other due to the construction of the adopted approach. With some simplification and as a first research iteration, this branching region, where no crack path information is obtained, can be modeled with a constant strain injection while the crack branches, with a clear directional localization, can be modeled with the strong discontinuity mode injection.

Due to the methodology interesting properties (flexibility, robustness, low computational cost, mesh independence, etc.) the team members are very optimist about the potential of the strain injection and crack path field techniques for modeling fast dynamic crack propagation. This optimism is further supported by some motivating preliminary results obtained recently [22], by members of the research team, in which dynamic simulations on a concrete specimen were performed, by increasing the loading rate up to the appearance of crack branching.

This task is not straightforward, but will allow interesting developments in this appealing field having potential impact in several fields of applications (e.g. computational design of materials, components and structures under dynamic loading regimes, computational safety assessment of existing structures under severe dynamic loads, like concrete dams, etc.).

Members of the research team in this task:

Oriol Lloberas-Valls, Ivo Dias and Javier Oliver

T3 – Extension to 3D

For obtaining a general methodology, a three dimensional implementation of the formulation is mandatory, since some structures cannot be analyzed over plane strain or plane stress simplifications. That is the case, for instance, of arch dams, that behave partly as a cantilever, a retaining wall standing up from its base, and partly as an arch, in which the hydraulic loads are transferred to the lateral bearings by horizontal arch action. This kind of 3 dimensional behavior cannot be modeled in only two dimensions.

Therefore, the specific goal of this task is to extend the methodology to 3 dimensions. The authors think that the strain-injection and the crack-path field technics do not have any critical theoretical limitation precluding this goal to be achieved. Nevertheless, extension to 3D requires various generalizations that have to be developed and implemented.

Again, the research team remarks, that even so the application field of this research project is mainly related to concrete dams, we intend to obtain a completely general methodology, such that all kind of structures and materials can be modeled. The strain injection techniques is based in improving the performance of those finite elements that are going to capture the cracks by using some enhanced strain modes. For that, some modifications/improvements at the level of the finite element formulation are implemented, but no changes/restrictions are made about the constitutive modeling. Therefore, in principle, any family of internal-variable based constitutive models (plastic models, continuum damage models, smeared cracking, *etc*.) can be used with no other limitation than their physical appropriateness for the considered problem.

In this task, the generality of the formulation will be pointed out and therefore, once the computational implementation is extended, to validate the applicability of the methodology, numerical representative simulations of a wide range of benchmarks, in terms of the type of material and the mechanical failure mechanism, will be performed.

This extension and implementation task is critical for the developing of the project, since task number 4, which consists in the analysis of arch dams under seismic loads, demand this generalization to be successfully implemented in the finite element code.

Members of the research team in this task:

Ivo Dias and Javier Oliver

T4 – Application to 3D Seismic failure analyses of concrete dams

The specific goal of this task is to evaluate the structural safety of large concrete dams when loaded with severe seismic actions. The goal of this task is oriented for helping in responding to very pertinent practical needs and concerns relatively to the safety assessment of this important structures, which failure during a strong seismic events can result in potential disastrous consequences in terms of life losses and strong environmental and economic impacts.

In fact, LNEC, as a reference institution in dam engineering is frequently requested about whether a dam is safety, or not, against the maximum expected earthquakes. However, in some cases, where the intensity of the seismic loads is particularly severe, is difficult to provide a definitive answer for this question, since some level of uncertain remains, at several levels, which include the numerical modeling of the failure mechanism.

During intensive earthquakes, the dynamic response of the dam is very complex involving, not only, the structural and the material dynamic characteristics which includes the non-linear effects coming from the contraction joint opening, but also effects related to the interaction with the external environment [23, 24]: (1) the effects of dam-reservoir interaction for considering the hydrodynamic loading; and (2) the effects of dam-foundation interaction which includes the modeling of the radiation damping due to the infinite canyon and the earthquake input mechanism.

These affects have been well studied in the literature and have to be implemented in the finite element code during the initial stages of this task. For that, at the beginning of the task, throughout a state of art study, the most suitable and effective methodologies for considering the aforementioned effects will be selected. For the constitutive material modeling there are, also, several options available in the literature. An interesting option is the continuum damage model proposed by Cervera and Oliver [25], that considers two scalar internal damage variables, allowing differentiating damage in tension and compression and exhibiting stiffness recovery upon load reversal.

After implementing all the needed ingredients, the strain injection and the crack-path field techniques will be used for modeling crack formation and propagation, during earthquakes, and its influence in eventual total, or partial, failure mechanism.

At the end of this research project, the methodology will allow a better failure modeling of concrete dams under seismic loads, helping on the safety assessment of existing structures and also in the design of less vulnerable new dams.

This task requires previous extension of the strain injection techniques for 3D cases and for including the inertial effects. This previous extensions are to be performed at the preceding tasks 2 and 3, respectively.
Members of the research team in this task:

Ivo Dias, Javier Oliver, José Vieira Lemos and Oriol Lloberas-Valls

T5 – Application to early detection of failure scenarios of concrete dams

The early detection of failure scenarios is an current interesting research topic [26] that emerges naturally from the increasing demanding of civil society in guaranteeing dam safety. This research task has the specific goal of contributing on this topic research by providing information about dam failures mechanisms, which is a current need for the developing of early detection systems.

Due to the high potential disastrous consequences in case of failure, large dams are continually monitored in time, as a part of the safety control process. The monitoring system, supported by numerical models that help in the interpretation, allows the control of the dam behavior over time, such that any unexpected malfunction can be detected and studied as earlier as possible.

With the advance of information technologies and due the higher safety requests from civil society in ensuring dam safety, automated monitoring systems are implemented in large dams [27]. These automated systems allow the dam behavior to be monitored in real time. However, for the monitoring system to be effective, a management system for real-time decision based in specific rules must, also, be implemented. One important application of this kind of systems is the early detection of eventual failure scenarios [26], which allows afterwards, the implementation of automatic emergence actions for mitigating the catastrophic consequences associated to an eventual sudden flood wave (opening dam gates for reducing reservoir level, warning to the population in valley, active civil protection emergence plans, etc.)

In this research task, a set of failure scenarios due to crack propagation through the dam body or at the interface dam/foundation, caused by different loading (e.g., dam overflow, ageing scenarios, etc.), will be solved by using the strain injection techniques. Then, decision rules for the early detection of failure scenarios will be constructed by using the information computed numerically by using the strain injection techniques (that describe the exceptional dam behavior in a failure scenario), the information provided by the monitoring system and the information characterizing the expected normal dam behavior.

Members of the research team in this task:

Juan Mata and Ivo Dias

T6– Software integration & Optimization

One of the overall goals of this project is to contribute for the developing and consolidation of the newly developed numerical techniques (crack-path-field and the strain-injection technics) such that, the strong potential of the methodology can be transformed in an effective tool for modeling material failure that can help engineers in the safety assessment of special important structures like large concrete dams.

This overall goal will be materialized in the software CoMatFail, that will be developed from a previously existent academic finite element software, that was developed and shared by CIMNE (http://www.cimne.com/compdesmat/), with the collaboration of the post-doc researcher Ivo Dias. For achieving this goal all the contributions developed during this research project must be integrated in a single stable and optimized branch of the finite element code.

Task 6 is then devoted to these implementation issues related to code maintenance, optimization and unification, and also to the integration of CoMatFail in GiD [28], by designing a new problem type (interface between GiD and the finite element code). GiD is a universal, adaptive and user-friendly pre and postprocessor for numerical simulations, developed in CIMNE, allowing pre and post-processing: geometrical modeling, effective definition of analysis data, meshing, data transfer to analysis software, as well as the visualization of numerical results. The integration in GiD is interesting for non-developing users (not familiarized with the finite element code), since they will be able to perform structural failure modeling analysis by using the user-friendly GiD interface, and also for expert users, since the productivity in the model generation can be improved.

Members of the research team in this task:

Ivo Dias and Oriol Lloberas-Valls

Financiamento e candidaturas:

Apesar de não existir atualmente qualquer fonte de financiamento externa ao LNEC, têm sido realizados esforços (que terão continuidade no futuro), por parte do investigador responsável do projeto CoMatFail, no sentido de conseguir financiar as atividades de investigação associadas ao projeto.

Em 2015 foi submetida uma candidatura conjunta entre o LNEC e o CIMNE, a um projecto FCT, que resultou da colaboração recente que tem vindo a ser realizada entre as duas instituições, no campo da mecânica computacional. O projeto não foi seleccionado para financiamento.

Mais recentemente, em julho de 2016, foi submetida uma candidatura a uma bolsa de Pós-doutoramento da FCT, por parte do investigador responsável do projeto CoMatFail (ref. SFRH/BPD/123283/2016). Esta candidatura, que se encontra em fase de análise por parte da FCT, poderia, em caso de ser vencedora, vir a financiar a actividade do investigador responsável (que corresponde a cerca de 80% dos custos do projeto).

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6 - Plano de Trabalhos

Data de inicio: 01-01-2016 *

Tarefa	Designação da Tarefa	2015 1º Sem.	2015 2º Sem.	2016 1º Sem.	2016 2º Sem.	2017 1º Sem.	2017 2º Sem.	2018 1º Sem.	2018 2º Sem.	2019 1º Sem.	2019 2º Sem.	Total em meses
T1	Application to failure analysis of concrete gravity dams											6
T2	Extension to fast dynamic crack propagation											15
T3	Extension to 3D											21
T4	Application to 3D seismic failure analyses of concrete dams											33
T5	Application to early detection of failure scenarios of concrete dams											12
T6	Software integration & optimization											18

* Notice that the first research tasks (T1, T2 and T3) are part of the recent and ongoing research of some team members, being these tasks at different degrees of development. For giving a panorama of the current progress of each task, the research performed in 2015 was included in the timeline of the project.

7 - Equipa de trabalho

Nome	Categoria	Setor/Entidade	Tarefas	Afetação ao projeto (%)
Ivo Dias	Bolseiro Pós-doc LNEC (BPD)	DBB/NMMR	Coordenação T1 - T6	45%
José Vieira Lemos	Investigador Coordenador	DBB/NMMR	T1 e T4	5%
Juan Mata	Bolseiro Pós-doc LNEC (BPD)	DBB/NO	T5	5%
	Escolher			
Javier Oliver	Escolher	CIMNE	T2, T3 e T4	
Oriol Llorebas-Vals	Escolher	CIMNE	T2, T4 e T6	
	Escolher			

8 - Resultados expectáveis

Resultados por atividade/tarefa	Descrição
(descrever os resultados esperados por actividade e/ou tarefas)	
T1 – Application to failure analysis of concrete gravity dams	The results obtained in this task are expected to show that the method is ready for being used in practice, allowing improved estimation of the structural safety factor and helping in the security control of those gravity concrete dams which might be particularly vulnerable for crack propagation. The main results of this task are to be published in 1 international journal paper.
T2 – Extension to fast dynamic crack propagation -	For a detailed simulation of structures loaded by seismic actions, the inertial effects cannot be discarded. Therefore, the extension proposed to be developed at this research task will open the application field to dynamic problems, such that fast propagating dynamic fracture can be studied. This task is a developing task which achievement is fundamental for developing the application task 4. The main results of this task are to be published in 1 international journal paper.
T3 – Extension to 3D	At the end of this research task we intend to obtain a three dimensional implementation of the formulation, so general structures can be studied. This extension and implementation task is critical for the developing of the project, since task number 4, which consists in the analysis of arch dams under seismic loads, demand this generalization to be successfully implemented in the finite element code. The mains results of this task are to be published in 1 international journal paper.
T4 – Application to 3D Seismic failure analyses of large concrete dams	The safety of concrete dams under severe seismic loads is still nowadays very difficult to assess, since some degree of uncertain remain, at several levels, which includes the numerical modeling of the failure mechanism. At the end of this research we expect to deliver a methodology allowing improved failure modeling under dynamic conditions, such that it can help engineers in performing better and more accurate analysis and previsions of the safety margins of dams subjected to severe seismic loads. The main results of this task are to be published in 1 international journal paper.
T5 – Application to early detection of failure scenarios of concrete dams	The early detection of failure scenarios is current interesting research topic [26] that emerges naturally from the increasing demanding of civil society in guaranteeing dam safety. This research task has the specific goal of contributing for this research topic by using the strain injections techniques for computing information about the potential dam failure mechanisms, and then integrating this information in the management systems for real-time control and decision. The main results of this task are to be published in 1 international journal paper.
T6 – Software integration & Optimization	One of the overall goals of this project is to “transform” the current academic open source software into an effective numerical tool for modeling propagating material failure. In this task the goal is to integrate all the implementation works in a unique branch of the finite element code while optimizing the nuclear code routines, such that an computational efficient implementation is achieved and a stable code version produced, complemented with a simple user manual.

Outros resultados	Quantidade
Teses	
mestrado	1
doutoramento	0
outras	0
Artigos em revista	
nacional	1
internacional	5
Comunicações	6
Outros produtos	
CoMatFail - Finite element software for Computational Material Failure analisys	1

9 - Recursos humanos

Grupo	Esforço (h*m)	Valor €
1	2,40	15 600,00
2	0,00	0,00
3	0,00	0,00
4	0,00	0,00
11	24,00	96 000,00
12	0,00	0,00
13	0,00	0,00
21	0,00	0,00
22	0,00	0,00
23	0,00	0,00
TOTAL	26,40	111 600,00

10 - Despesas correntes

Designação	Quantidade	Valor unitário €	Montante €
			0,00
			0,00
			0,00
			0,00
			0,00
			0,00
TOTAL			0,00

11 - Equipamento

Designação	Quantidade	Valor unitário €	Montante €
			0,00
			0,00
			0,00
			0,00
			0,00
			0,00
TOTAL			0,00

12 - Orçamento

Designação	Estimativa de custo €	Financiamento externo €	Financiamento LNEC €
Recursos Humanos	111 600		111600
Despesas Correntes	0		0
Equipamentos	0		0
Gastos gerais	111 600		111600
			0
			0
Total	**223 200**	**0**	**223 200**