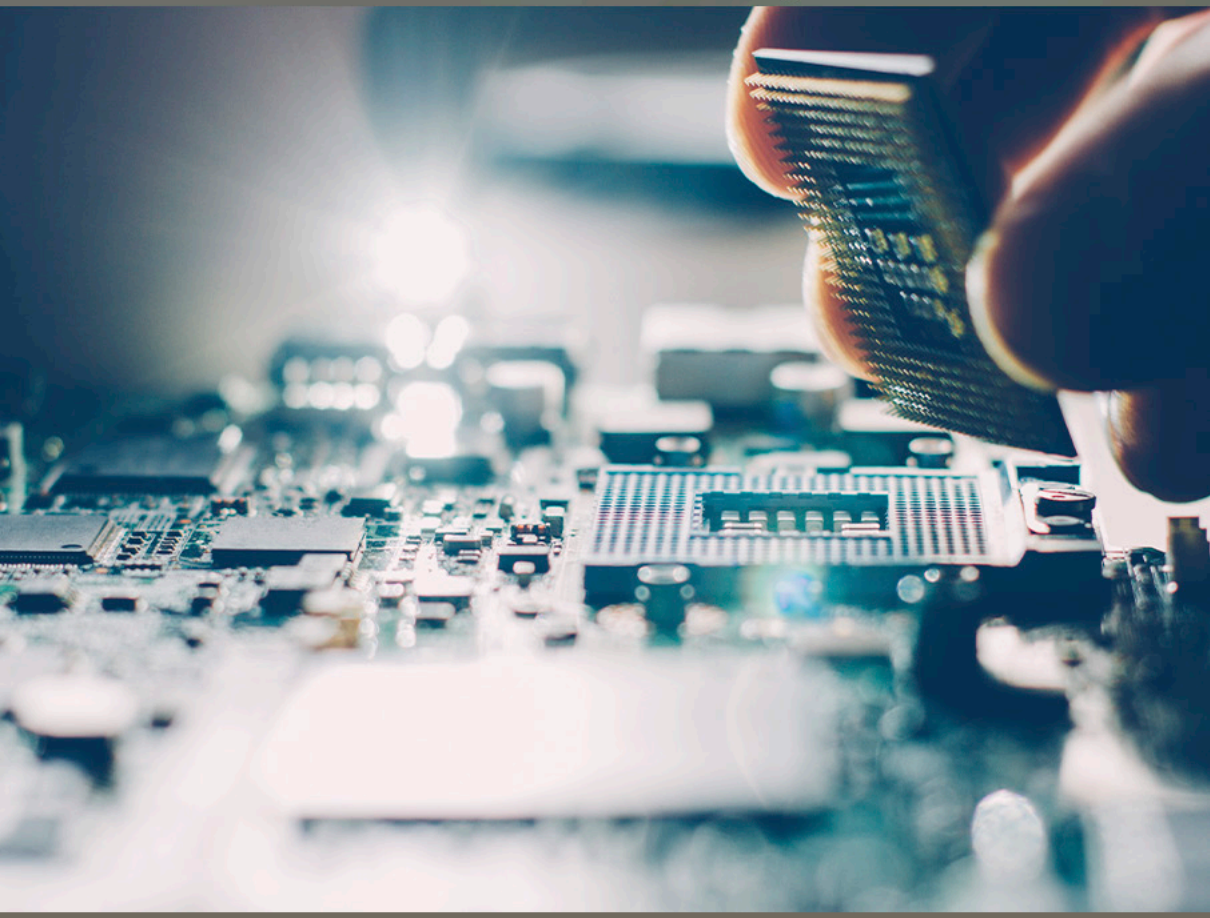
COLEÇÃO

DESAFIOS DAS ENGENHARIAS:

ENGENHARIA DE COMPUTAÇÃO 3



LILIAN COELHO DE FREITAS
(ORGANIZADORA)

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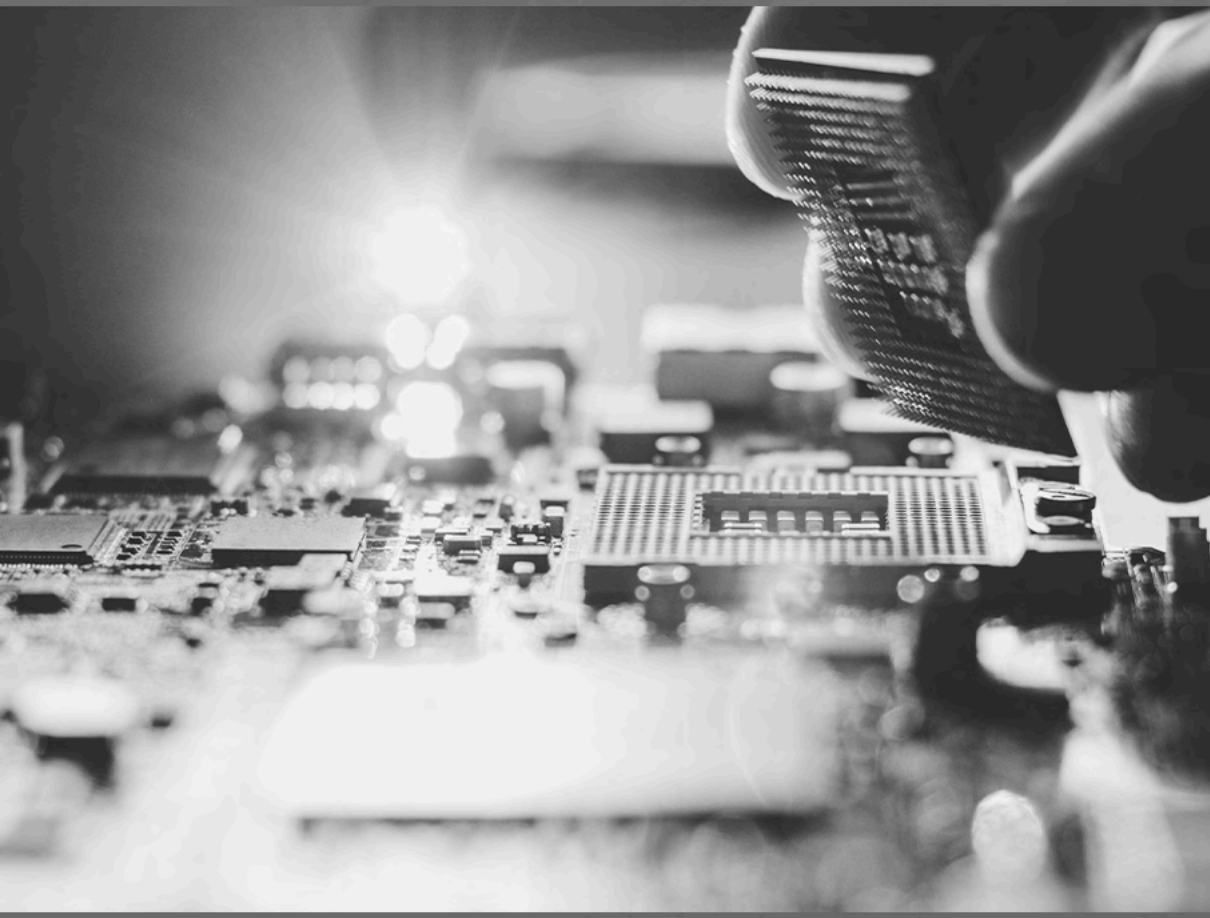

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APRESENTAÇÃO

A Atena Editora tem a honra de presentear o público em geral com a série de *e-books* intitulada "*Coleção desafios das engenharias: Engenharia de computação*". Em seu terceiro volume, esta obra tem o objetivo de divulgar aplicações tecnológicas da Engenharia de Computação na resolução de problemas atuais, com o intuito de facilitar a difusão do conhecimento científico produzido em várias instituições de ensino e pesquisa do país.

Organizado em 20 capítulos, este volume apresenta temas como utilização de aprendizagem de máquina na avaliação de riscos de infeção por COVID-19; dispositivos automatizados para administração de remédios; comunicação científica apoiada por realidade aumentada; métodos de elementos finitos aplicados na análise de materiais para indústria aeronáutica; aplicações de processamento digital de imagens e de algoritmos genéticos; entre diversas outras aplicações da automação e do desenvolvimento de *software,* combinados para melhorar as atividades do nosso dia-a-dia.

Dessa forma, esta obra contribuirá para aprimoramento do conhecimento de seus leitores e servirá de base referencial para futuras investigações.

Os organizadores da Atena Editora, agradecem especialmente os autores dos diversos capítulos apresentados, parabenizam a dedicação e esforço de cada um, os quais viabilizaram a construção deste trabalho.

Boa leitura.

Lilian Coelho de Freitas

SUMÁRIO

CAPÍTULO 19

LOCAL MESHFREE METHOD OPTIMIZATION WITH GENETICALGORITHMS

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ABSTRACT: This paper is correlated to the optimization of two local meshfree methods, Local Meshfree method with reduced integration (ILMF) and the Meshless Local Petrov-Galerkin (MLPG) method. In order to optimize those methods, it is applied Genetic Algorithms (GA). As a consequence of it, these numerical methods become faster and more accurate, which is a feature of paramount importance as far as the computational efficiency is concerned. The accuracy and efficiency of local meshfree methods are determined by two parameters of discretization which are the compact support and the local integration domain. The size of both parameters is what determine the accuracy and efficiency of the method. The first parameter is primarily linked to the model accuracy, yet the second parameter is linked to the model efficiency. In this paper, those parameters of discretization are automatically defined through a multi-objective optimization process based on genetic algorithms. A test problem was analyzed with those techniques, in order to evaluate the accuracy and efficiency of these meshfree numerical methods. A numerical assessment of the effect of the irregularity of the nodal distribution referred to by the parameter (Cn), is presented in the paper. The numerical results were obtained to s show the high level of accuracy when it is compared to the exact solution.

KEYWORDS: Local meshless method, Local Meshfree method with reduced integration (ILMF), Meshless Local Petrov-Galerkin (MLPG), Genetic Algoritms (GA).

MÉTODO SEM MALHA LOCAL OPTIMIZADO COM ALGORITMOS GENÉTICOS

RESUMO: Este trabalho está correlacionado à otimização de dois métodos locais sem malha, o método Local sem malha com integração reduzida (ILMF) e o método sem malha Local Petrov-Galerkin (MLPG). Para otimizar esses métodos, são aplicados Algoritmos Genéticos (AG). Como consequência, esses métodos numéricos tornam-se mais rápidos e precisos, o que é uma característica de suma importância no que diz respeito à eficiência computacional. A precisão e eficiência dos métodos sem malha local são determinadas por dois parâmetros de discretização que são o suporte compacto e o domínio de integração local. O tamanho

de ambos parâmetros é o que determina a precisão e eficiência do método. O primeiro parâmetro está principalmente ligado à precisão do modelo, mas o segundo parâmetro está ligado à eficiência do modelo. Neste artigo, esses parâmetros de discretização são definidos automaticamente por meio de um processo de otimização multiobjetivo baseado em algoritmos genéticos. Um problema de uma viga foi analisado com essas técnicas, a fim de avaliar a precisão e eficiência desses métodos numéricos sem malha. Uma avaliação numérica do efeito da irregularidade da distribuição nodal referida pelo parâmetro (Cn), é apresentada no artigo. Os resultados numéricos foram obtidos para mostrar o alto nível de precisão quando comparado à solução exata.
PALAVRAS-CHAVE: Método sem malha local, método sem malha local com integração reduzida (ILMF), método sem malha local Petrov-Galerkin (MLPG), Algoritmo genético (AG).

1 I INTRODUCTION

Numerical methods based on grids, as the finite element method (FEM), are widely used in engineering and science. Grid based methods required high quality meshes when solving fracture mechanics problems, with material discontinuities, nonlinear problems, with large displacements, where excessive mesh distortion takes place. On the other hand, meshfree methods were developed with the expectation of providing more adaptive, accurate and stable numerical solutions, to deal with problems where conventional grid-based methods are not well suited, (Daxini and Prajapati, 2014). In general, their formulation is based in the weighted residual method, (Finalyson, 1972).

Different meshless methods have been developed during the last 20 years, (Chen et al, 2017). Some of these methods, based on a weighted residual global weak form, were applied in solid mechanics, such as the diffuse element method (DEM), the reproducing kernel particle method (RKPM) and the element free Galerkin (EFG). Other methods emerged based on weighted residual local weak forms, such as the meshless local Petrov-Galerkin method (MLPG), the meshless local boundary integral equation method (MLBIE), the local point interpolation method (LPIM), the local radial point interpolation method (LRPIM), the meshless finite volume method (FVM), the rigid body displacement meshfree method (RBDMF) and the generalized strain meshfree method (GSMF), (Oliveira and Portela, 2016).

Meshless Local Petrov-Galerkin (MLPG) method, the most popular of these methods, is based on a moving least squares approximation (MLS). The main difference of the MLPG method to other global meshless methods, the method does not require the use of a background global mesh, but only a background local grid, using the MLS approximation. The reduced integration, a key feature of this formulation, induces a reduction of the nodal stiffness which, in turn, increases the solution accuracy, as a consequence of the theorem of the minimum total potential energy.

The accuracy and efficiency of local meshfree methods is determined by two discretization parameters. The size of the compact support of each node, that is primarily linked to the accuracy of the model through the total number of nodes used to build the

shape functions of the local node stiffness and, the size of the local domain of each node where the work theorem is numerically integrated, that is primarily linked to the efficiency of the model.

These meshfree discretization parameters are obviously very important and greatly affect the performance and accuracy of a meshfree analysis. Both parameters are usually arbitrarily defined and can vary depending on the local meshfree method used, which is the reason why they are generally presented alongside new meshfree methods.

The optimization using genetic algorithms (GA), on MLPG was performed for two dimensional steady-state heat conduction problems (Atluri and Zhu, 2000) and for three dimensional elastostatic problems (Liu and Gu, 2005). A similar optimization was proposed, combined with an additional adaptive refinement technique using the MLPG-FVM (Ebrahimnejad et al, 2015). Although these authors were successful, their attempt led to a very time-consuming approach that requires an analytical solution to be performed and therefore is not efficient. The basic ideas and terminology of single- and multi-objective optimization are formally defined in optimization literature (Hwang et al, 1979; Sawaragi et al, 1985; Steuer et al, 1986; and Ringuest et al, 1992). It is studied the multi-objective optimization problem (MOP) and it contains a set of n decision variables, a set of k objective functions, and a set of m constraints. Objective functions and constraints are functions of the decision variables, in this case α_q and α_s.

Among the recent researches elaborated by the Post-Graduate Program in Structures and Civil Construction of the University of Brasília, the ones that will be briefly presented below stand out. Oliveira et al. (2019) calculated the stress intensity factors in problems of linear elastic fracture mechanics using regular and irregular meshes of a non-local mesh method. Vélez (2019) presented a local numerical method for irregular nodal configuration. Santana et al. (2020) presented the automation of the parameters of a non-mesh method. Oliveira et al. (2020) formulated a local numerical method for linear elastic problems. Araújo et al. (2021) presented an automated meshless method with an irregular nodal configuration.

This work is concerned on the size effect of the irregularity of the nodal arrangement, referred to by the irregularity parameter (Cn), when the discretization is considered with fixed values of the local support domain (α_s) and the local quadrature domain (α_q). The work presents a comparison of the energy relative error for three different irregular nodal distributions used to solve the benchmark problem of the Timoshenko cantilever beam. Results obtained with ILMF and MLPG using genetic algorithms in the ILMF model are compared with the exact solution. Optimal results were obtained.

2 | METHODOLOGY

Let Ω be the domain of a body and Γ its boundary, subdivided in Γ_u and Γ_t that is $\Gamma = \Gamma_u \cup \Gamma_t$; in the Figure 1 show the nodal points P, Q and R have corresponding local domains Ω_P,

Ω_Q, and Ω_R. The general fundamental boundary value problem of linear elastostatics aims to determine the distribution of stresses σ, strains ε and displacements u, throughout the body, when it has constrained displacements , on Γ_u and it is loaded by an external system of distributed surface and body forces with densities denoted, respectively by , on Γ_t and b, in Ω.

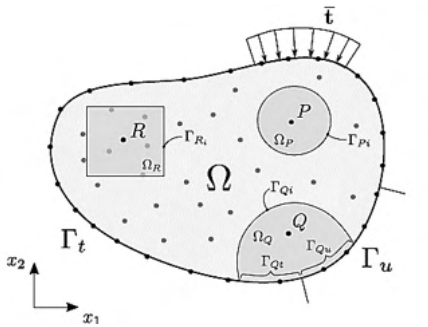


Figure 1. Global domain Ω and the local domains ΩP, ΩQ and ΩR, with boundary Γ = Γu U Γt represented.

The solution of these problem is a totally admissible elastic field that simultaneously satisfies the kinematic admissibility of the strains and the static admissibility of the stresses. If this solution exists, it can be shown that it is unique, provided linearity and stability of the material are admitted. Such is the Kirchhoff's theorem, on the uniqueness of solutions of the elastostatic boundary value problem. For the sake of generality, the solution of the posed problem is derived through the work theorem. In the body's domain Ω consider a statically admissible stress field **σ**, which is any stress field that satisfies the equilibrium with the system of applied external forces which therefore satisfies

$$\mathbf{L}^T\sigma + b = 0, \tag{1}$$

in the domain Ω, with boundary conditions

$$\mathbf{t} = \mathbf{n}\boldsymbol{\sigma} = \bar{\mathbf{t}}, \tag{2}$$

on the static boundary Γ_t, in which **L** is a matrix differential operator; **t** is the vector of traction components; is the vector of the prescribed tractions and **n** is the matrix of the components of the unit outward normal to the boundary. In the domain Ω consider an arbitrary local domain Ω_Q, assigned to a reference point Q Є Ω_Q, with local boundary Γ = Γ_{Qi} U Γ_{Qt} U Γ_{Qu}, Γ_{Qi}, in which Γ_{Qi} is the interior local boundary, while Γ_{Qt} and Γ_{Qu} are local boundaries that share the global boundaries, respectively the static boundary Γ_t and the kinematic boundary Γ_u, as represented in Figure 1. The work theorem will be used as a local form that is valid in the arbitrary local domain Ω_Q. Due to its arbitrariness, this local domain $\Omega_Q \cup \Gamma_Q$ Ω ∪ Γ can be overlapping with other similar sub-domains that can be defined in

the body.

The work theorem establishes an energy relationship, valid in an arbitrary local domain $\Omega_Q \in \Omega$, between two independent elastic fields that can be defined in the body which are, respectively a statically admissible stress field that satisfies equilibrium with a system of external forces, and a kinematically admissible strain field that satisfies the compatibility with a set of constrained displacements. Derived as a weighted residual statement, the work theorem serves as a unifying basis for the formulation on numerical models Continuum Mechanics, Brebbia and Tottenham [14]. Expressed as an integral local form, defined in the local domain Ω_Q, the work theorem can be written in a compact form, simply as

$$\int_{\Gamma_Q} \mathbf{t}^T \mathbf{u}^* d\Gamma + \int_{\Omega_Q} \mathbf{b}^T \mathbf{u}^* d\Omega = \int_{\Omega_Q} \boldsymbol{\sigma}^T \boldsymbol{\varepsilon}^* d\Omega, \tag{3}$$

in which the stress field **σ** and the strain field are not linked by any constitutive relationship and therefore, they are independent of each other. The statically admissible stress field **σ** can be any stress field that is in equilibrium with the system of applied external forces, therefore satisfying equations. (1) e (2), which is not necessarily the stress field that the system of applied external forces introduces in the body. The kinematically admissible strain field **ε*** can be any strain field defined in the body, generated by continuous displacements **u*** with small derivatives, compatible with an arbitrary set of constraints specified on the kinematic boundary, which is not necessarily the strain field that actually settles in the body. Finally, the local domain Ω_Q is any arbitrary sub-domain of the body, associated to the reference point Q, as represented in Figure 1, where the independent fields **σ** and **ε*** can be defined. Kinematic formulations consider, in the work theorem, a particular and convenient specification of the kinematically admissible strain field, leading thus to an equation of mechanical equilibrium that is used to generate the stiffness matrix of the numerical model. Bearing in mind the essential feature of the work theorem, which is the complete independence of the stress field **σ** and the strain field **ε***, the strain field can be conveniently defined by a rigid-body displacement

$$\mathbf{u}^*(\mathrm{x}) = \mathbf{c}, \tag{4}$$

where **C** is a constant vector that conveniently leads to null strains that is

$$\boldsymbol{\varepsilon}^*(\mathrm{x}) = \mathbf{0}. \tag{5}$$

When this kinematic formulation is considered, the local form of the work theorem, eq. (3), simply leads to the equation

$$\int_{\Gamma_Q - \Gamma_{Q_0}} \mathbf{t}\, d\Gamma + \int_{\Gamma_{Q_0}} \bar{\mathbf{t}}\, d\Gamma + \int_{\Omega_Q} \mathbf{b}\, d\Omega = 0, \tag{6}$$

which states an integral form of mechanical equilibrium, of tractions and body forces, in the local domain Ω_Q, are represented in Figure 2. This equation expresses the local version of the basic Euler-Cauchy stress principle that is sometimes referred to as the defining principle of continuum mechanics.

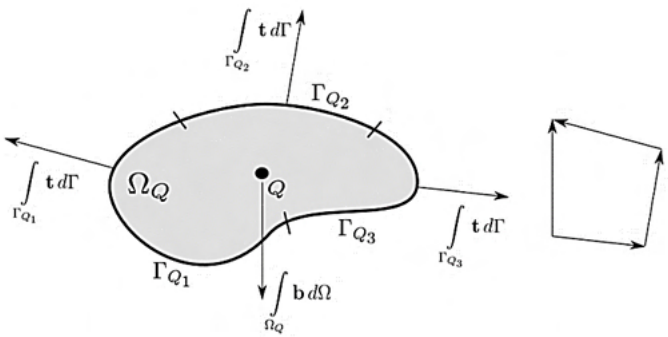


Figure 2. Schematic representation of the equilibrium of tractions and body forces.

The modeling strategy, adopted to solve the actual elastic problem, considers that the stress field **σ**, required to satisfy the equilibrium with a system of external forces, is assumed as the stress field that actually settles in the body, when it is loaded by the actual system of external distributed surface and body forces, with the actual displacement constraints. Recall that the elastic field that actually settles in the body is the unique fully admissible elastic field that satisfies the given problem. Therefore, besides satisfying static admissibility, through equations (1) and (2), that is the same as satisfying equilibrium through eq. (6), generated by the weak form eq. (3) of the work theorem, this unique fully admissible elastic field also must satisfy kinematic admissibility defined as

$$\varepsilon = \mathbf{L}\mathbf{u}, \tag{7}$$

in the domain Ω, with boundary conditions

$$\mathbf{u} = \overline{\mathbf{u}}, \tag{8}$$

on the kinematic boundary Γ_u, in which the displacement **u** is assumed continuous with small derivatives, in order to allow for geometrical linearity of the strain field ε. Hence, equation (8), which specifies the constraints of the actual displacements, must be enforced in any numerical model, in order to provide a unique solution of the elastic problem. For the sake of simplicity, this paper considers the formulation of the ILMF model in the absence of body forces. Consequently, the nodal equations of equilibrium are always defined only on the boundary of the local domain.

The meshless method with reduce integration is based on the widely used moving least-squares (MLS) approximation, introduced by Atluri and Zhu [15]. The MLS approximation is one of the best methods to approximate data with a good accuracy. The definition domain contains all the nodes whose MLS shape functions do not vanish at this sampling point. Therefore, the domain of influence of each node, is the union of the MLS domains of definition of all points in the local domain of the node. Finally, local mesh free formulations use a node-

by-node stiffness calculation to generate, in the domain of influence of the local node, the respective rows of the global stiffness matrix.

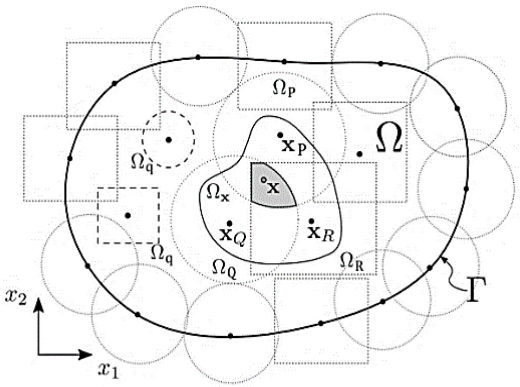


Figure 3. Representation of a global domain Ω and boundary.

3 I INTEGRATED LOCAL MESH FREE METHOD (ILMF)

Assuming a variation linear of the tractions along each boundary segment of the local domain, the local integral form of equilibrium can be evaluated with a single quadrature point, centered on each segment of the boundary, Figure 4. Applying this linear integration process in the Eq. (7), the following expression is obtained

$$-\frac{L_i}{n_i}\sum_{j=1}^{n_i}\bar{\mathbf{t}}_{x_j}=\frac{L_i}{n_i}\sum_{j=1}^{n_i}\bar{\mathbf{t}}_{x_k}+\int_{\Omega_Q}\mathbf{b}\,d\Omega \tag{9}$$

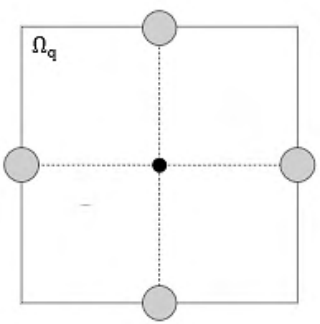


Figure 4. Schematic representation of numerical quadrature, of local ILMF domain.

For a given nodal distribution, Equation (9) can be presented as follows

$$-\frac{L_i}{n_i}\sum_{i=1}^{n_i}\mathbf{n}_{x_j}\mathbf{DB}_{x_j}\hat{\mathbf{u}}=\frac{L_t}{n_t}\sum_{j=1}^{n_t}\bar{\mathrm{t}}_{x_k}+\int_{\Omega_Q}\mathbf{b}\,\mathrm{d}\Omega \tag{10}$$

which can be written as

$$\mathbf{K}_Q\hat{\mathbf{u}}=\mathbf{F}_Q \tag{11}$$

where K_Q, the nodal stiffness matrix associated with the Q field node, is a 2x2n matrix (n is the number of nodes included in the reference domain influence Q node which is the union of all definition MLS domains integration points in the local domain Ω_Q) given by

$$\mathbf{K}_Q=-\frac{L_i}{n_i}\sum_{i=1}^{n_i}\mathbf{n}_{x_j}\mathbf{DB}_{x_j}\hat{\mathbf{u}} \tag{12}$$

and $\mathbf{F}_Q$ is the respective force vector given by

$$\mathbf{F}_Q=\frac{L_t}{n_t}\sum_{j=1}^{n_t}\bar{\mathrm{t}}_{x_k}+\int_{\Omega_Q}\mathbf{b}\,\mathrm{d}\Omega \tag{13}$$

Consider that the problem has a total of N field nodes Q, each one associated with the respective local region Ω_Q. Assembling eq. (11), for all M interior and static – boundary field nodes lead to the global system of 2M x 2N equations

$$\mathbf{K}\hat{\mathbf{u}}=\mathbf{F}. \tag{14}$$

Finally, the remaining equations are obtained from the N – M boundary field nodes on the kinematic boundary. For a field node on the kinematic boundary, a direct interpolation method is used to impose the Kinematic boundary condition as equations

$$u_k(\mathrm{x}_j)=\sum_{i=1}^{n}\phi_i(\mathrm{x}_j)\hat{u}_{ik}=\bar{\mathbf{u}}_k, \tag{15}$$

Or, in matrix form as equations

$$\mathbf{u}_k=\sum_{i=1}^{n}\Phi_k\hat{\mathbf{u}}=\bar{\mathbf{u}}_k, \tag{16}$$

with k = 1, 2, where $\bar{\mathbf{u}}_k$ is specified nodal displacement component. Equations (12) are directly assembled into the global system of eq. (16).

4 | PARAMETERS OF THE MESHLESS DISCRETIZATION

For each node of a mesh free discretization, the size rΩs of the compact support Ωs, where shape functions are defined, and the size rΩq of the local integration domain Ωq, where the work theorem is defined, are very important parameters that can affect the performance of the solution of a numerical application. For a generic node i, these parameters can be defined as

$$r\Omega_S = \alpha_S d_i, \tag{17}$$

$$r\Omega_q = \alpha_q d_i, \tag{18}$$

in which ci represents the distance of the node i, to the nearest neighboring node, while αs and αq are arbitrary constant parameters that must be defined in any application. To improve the accuracy of a mesh free numerical application, the discretization requires a proper refinement of $r\Omega_s$ and $r\Omega_q$, through the specification of the arbitrary parameters αs and αq defined in equations, respectively (17) and (18). In general, the discretization parameters are considered, respectively as αs > 1.0 and αq < 1.0. The discretization parameters, αs and αq, play different roles in the local mesh free numerical application, but the most important quality for this work is that, the parameter αq, is primarily linked to the accuracy of the mesh free application and parameter αs, sometimes referred to as local domain discretization parameter, is linked to the efficiency of the application. Historically, discretization parameters have been heuristically defined and their value depends mostly on the MLS approximation and on the pattern of the nodal distribution of the mesh free application. However, the appropriate values of discretization parameters, α_s and α_q for irregular arrangement, are obtained automatically, through a multi-objective optimization process, performed with GA.

5 | IRREGULAR NODAL ARRANGEMENT

The nodal irregularity is generated by changing randomly the coordinates of the nodal regularity distribution by small distance, this movement can be calculated by

$$x_{1i}{}' = x_{1i} \pm c_n d_{x_{1i}}, \tag{19}$$

$$x_{2i}{}' = x_i \pm c_n d_{x_{2i}}, \tag{20}$$

in which Cn is a parameter that controls the nodal irregularity and vary randomly in the range of 0.0 and 0.4. For nodes located in the boundary there are restrictions that depend on the position of the node.

6 | NUMERICAL EXAMPLE

This section presents some numerical results to illustrate the accuracy and efficiency of the ILMF model, for the cantilever beam benchmark, considering different nodal configurations. The effect of the irregularity parameter of the nodal arrangement is analyzed and compared with MLPG and exact solution. The L2 energy norm and the relative error for $\|\varepsilon\|$ can be defined,

$$\|\varepsilon\| = \left[\frac{1}{2}\int_{\Omega} \varepsilon^T D\varepsilon d\Omega\right]^{1/2} \tag{21}$$

$$r_{\varepsilon} = \frac{\left\|\varepsilon_{num} - \varepsilon_{exact}\right\|}{\left\|\varepsilon_{exact}\right\|} \tag{22}$$

As a benchmark problem show in Figure 5. The beam is assumed in a plane stress state and the parabolic traction is

$$\bar{t}_2(x_2) = -\frac{P}{2I}\left(\frac{D^2}{4} - x_2^2\right), \tag{23}$$

where $I = D^3/12$ is the moment of inertia.

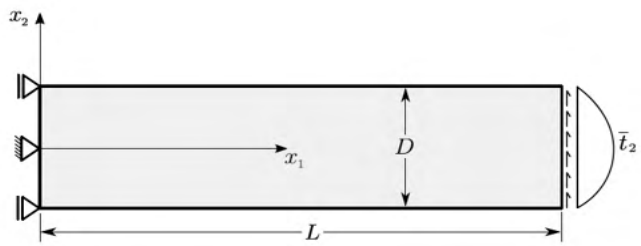
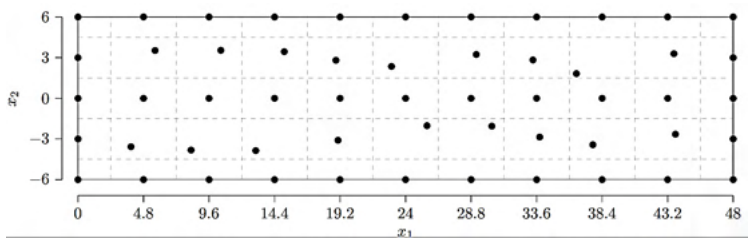


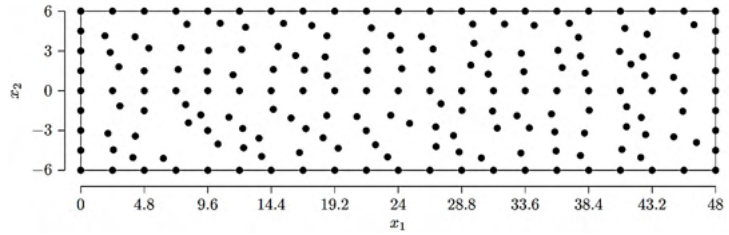
Figure 6. Cantilever beam.

Material properties are taken as Young's modulus E = 3.0 x 107 and the Poisson's ratio v = 0.3 and the beam dimensions are D = 12, L = 48 and thickness t = 1. The shear force is P = 1000.

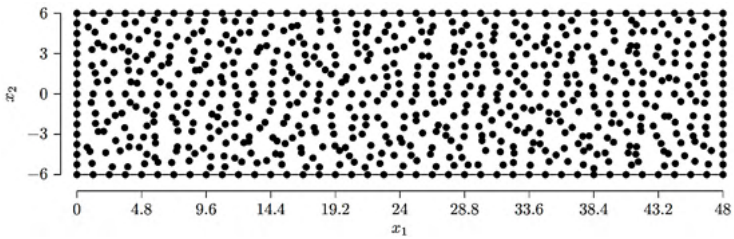
In order to solve this problem, the approach used was regular and irregular nodal distributions of discretization's with 55 (11×5), 189 (21×9) and 697 (41x17) nodes. The Figure 7 shows three nodal distributions of the beam discretization with fixed local domain, in which, the boundary nodes have a regular distribution.



(a) 55 nodes



(b) 189 nodes



(c) 697 nodes

Figure 7. Nodal distribution of the Cantilever beam discretization nodes with Cn = 0.4.

In the Figure 8 is shown the results obtained for the irregularity with fixed local domain with $\alpha_s = 2.12$ and $\alpha_q = 0.5$. To each Cn were made twelve graphic analysis and the result for the point is the normal average from these data.

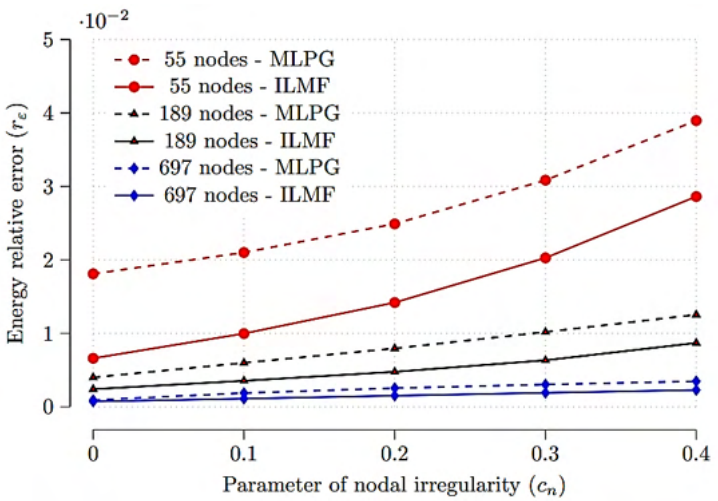


Figure 8. Energy relative error of ILMF and MLPG computed as a function of Cn.

Analyzing the Figure 8 it is easy to visualize the high level of accuracy from the results. Therefore, the outcomes from the analyses confirm the outstanding accuracy of both methods,

even for slight irregular nodal distributions.

In the Figure 9, the results obtained for the irregularity using genetic algorithms for both methods are shown. In this study, the genetic algorithm has the objective to reach the optimal values for αq and αs; in order to achieve this optimization, the function used is the energy relative error. To each Cn were made eight analysis and the result for the point is the average from these data. In addition, it was spent twenty minutes, approximately, for each value of Cn.

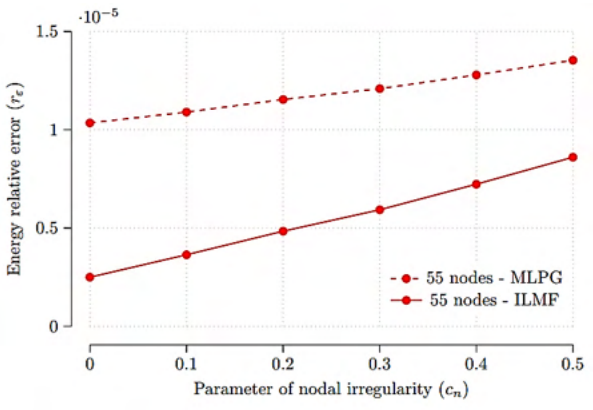


Figure 9. Energy relative error of ILMF and MLPG computed as a function of Cn using Genetic Algoritms.

Comparing the Figure 8 and the Figure 9, it can be seen that the results from the solution using genetic algorithms presented more accuracy than the discretization for both local methods without the optimization of the genetic algorithm. For example, the discretization with 55 nodes using genetic algorithm presented an error less than $1.5x10^{-5}$, yet the discretization with more nodes (697), using the ILMF and MLPG without the genetic algorithm optimization, presented an error of, approximately, 10^{-4}. In addition, it is visible that the IMLF displayed a better accuracy than the MLPG, in general.

7 | CONCLUSIONS

It can be seen that when larger is the number of nodes better is the accuracy of the results. In addition, it is noticeable that there is a direct relation between the coefficient Cn and the error. Another important conclusion from this figure is that the IMLF presents more accurate results than when a smaller number of nodes is used.

The genetic algorithms are a great tool to improve the accuracy of problems with irregularity nodal arrangement. Thus, this procedure avoids the use of a large number of nodes to solve the problem of the Cantilever Beam.

The use of genetic algorithms with local meshfree methods allows it to have a

more stable behavior in the solution of problems with nodal irregularity. Additionally, it also agrees with having an irregularity parameter Cn = 0.5.

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