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The weighted finite element method for the Lamé system in 2D cracked domain

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Abstract. In the present paper a boundary value problem for the Lamé system in the 2D cracked domain is considered. The solution to this problem is defined as $R$-generalized one in the weighted functional set. For determining of approximate solution, the weighted finite element method is built. Numerical analysis of the model problem showed that convergence rate of the approximate $R$-generalized solution to the exact one in the norm of the weighted Sobolev space has the first order that is twice greater than for the classical finite element method.

1. Introduction
Cracks frequently appear during production and use of different materials, parts and building structures. Presence of cracks has a great influence on durability of the constructions and a catastrophic consequence could arise from appearance and growth of cracks.

In many cases, a Lamé system is used as a foundation for mathematical modeling of the linear elastostatics in the cracked domain. In recent 30 years, on the base of classic works (see, for example, [1-4]) many researches of properties of solutions to the Lamé equations posed in the cracked or non-convex domains were performed, asymptotic expansion of the solutions near singularity points were obtained (see, for example, [5-7]). Taking into account these results and on the base of weak statement of the problem, many special numerical methods with the convergence speed $O(h)$ in the norm of Sobolev space $W^1_2(\Omega)$ were developed, such as: smoothed FEM [8] is based on the on the modification of the strain field; DPG FEM [9] suppose simultaneous approximation of the displacement and stress fields; extended FEM (Xfem) [10-11] is based on the addition of special function into the finite element space.

In the present paper, a boundary value problem for the Lamé system posed in 2D cracked domain is considered. The solution to this problem is defined as $R$-generalized one [12-16] in the special weighted functional set. For the numerical treatment of the problem, the weighted finite element method is constructed [17-21]. Numerical experiment for the model problem is performed and a comparison of the weighted FEM with the classic FEM is carried out. Results of the series of computations showed that the approximate $R$-generalized solution converges to the exact one in the norm of the weighted Sobolev space with the rate $O(h)$, that is twice greater than for the classical finite element method.
2. Problem statement

Let $\Omega = [-1,1] \times [-1,1]$ be a homogeneous isotropic body with the straight crack $[0,1] \times \{0\}$, $\partial \Omega$ is a boundary of the $\Omega$. In addition to the Cartesian coordinate system we also introduce polar coordinates with pole in the origin $(0,0)$ and polar axis codirectional with the $Ox$ axis (Fig. 1).

![Cracked domain](image)

Figure 1. Cracked domain.

Assume that the strains are small. In $\Omega$ consider a boundary value problem for the Lamé system (see [10]):

$$-(2 \text{div}(\mu \varepsilon(u))) + \nabla(\lambda \text{div}u) = f, \quad x \in \Omega,$$

$$u_i = q_i, \quad i = 1, 2, \quad x \in \partial \Omega \tag{1}$$

Here $u = (u_1, u_2)$ is the displacement field, $\varepsilon(u)$ is the deformation tensor.

Denote $\Omega' = \{ x \in \overline{\Omega} : (x_1^2 + x_2^2)^{1/2} \leq \delta < 1 \}$ a $\delta$-neighborhood of the $(0,0)$. We introduce the weight function $\rho(x)$ which coincides with the distance to the origin in $\Omega'$ and equals to $\delta$ for $x \in \Omega \setminus \Omega'$.

Denote $W^{1,2}_{\lambda,\Omega}(\Omega, \delta)$ the weighted set of functions satisfying the following conditions:

a) $|D^2 u(x)| \leq c_1 (\delta / \rho(x))^\alpha x_k$ for $x \in \Omega'$, where $k = 0, 1$ and $c_1$ - positive constant independent on $x$;

b) $\|u\|_{W^{1,2}_{\lambda,\Omega}(\Omega, \delta)} \geq c_2 > 0$

with the norm

$$\|u\|_{W^{1,2}_{\lambda,\Omega}(\Omega)} = \left( \int |D^2 u(x)|^{2 \lambda} dx \right)^{1/2},$$

where $D^2 = \frac{\partial^2 |v|}{\partial x_1 \partial x_2}, \quad \lambda = (\lambda_1, \lambda_2), \quad |\lambda| = \lambda_1 + \lambda_2; \quad \lambda_1, \lambda_2$ are nonnegative integers, $\alpha$ is some nonnegative real number. Denote $L^{1,2}_{\lambda,\Omega}(\Omega, \delta)$ the set of functions satisfying conditions (a) and (b) with the norm $\|u\|_{L^{1,2}_{\lambda,\Omega}(\Omega)} = \left( \int |D^2 u(x)|^{2 \lambda} dx \right)^{1/2}$. The set $W^{1,2}_{\lambda,\Omega}(\Omega, \delta) \subset W^{1,2}_{\lambda,\Omega}(\Omega, \delta)$ is defined as the closure in the norm (3) of the set $C_0(\Omega, \delta)$ of infinitely differentiable and finite in $\Omega$ functions which satisfy conditions (a) and (b).

We will say that $\phi \in W^{1,2}_{\lambda,\Omega}(\Omega, \delta)$ if there exists a function $\Phi \in W^{1,2}_{\lambda,\Omega}(\Omega, \delta)$, such that $\Phi(x)|_{\partial \Omega} = \phi(x)$ and $\|\phi\|_{W^{1,2}_{\lambda,\Omega}(\Omega, \delta)} = \inf_{\Phi \in W^{1,2}_{\lambda,\Omega}(\Omega, \delta)} \|\Phi\|_{W^{1,2}_{\lambda,\Omega}(\Omega, \delta)}$. For the corresponding spaces and sets of vector-functions we use notations $W_{\lambda,\Omega}(\Omega, \delta), L_{\lambda,\Omega}(\Omega, \delta), W^{1}_{\lambda,\Omega}(\Omega, \delta), W^{1,2}_{\lambda,\Omega}(\Omega, \delta)$.

Assume that the right hand sides of (1) and (2) meet the following conditions:

$$f \in L^{1,2}_{\lambda,\Omega}(\Omega, \delta), \quad q_i \in W^{1,2}_{\lambda,\Omega}(\partial \Omega, \delta), \quad i = 1, 2, \quad \beta > 0. \tag{4}$$

Introduce bilinear and linear forms respectively:

$$a(u, v) = \int_{\Omega} \sigma(u) : \varepsilon(v) dx, \quad l(v) = \int_{\Omega} \rho^\delta \mathbf{f} v dx.$$
Here \( \sigma(u) \) denotes the stress tensor.

**Definition 1.** A function \( u_h \in W^2_{0,\delta}(\Omega,\delta) \) is called an \( R_\delta \)-generalized solution to the problem (1),(2), if almost everywhere on \( \partial \Omega \) it satisfies boundary conditions (2) and for any \( v \in W^1_{2,\delta}(\Omega,\delta) \)

the integral identity

\[
a(u_h,v) = l(v)
\]

holds for any fixed value of \( v \), satisfying the inequality \( v \geq \beta \).

3. **Weighted finite element method**

For the problem (1),(2) on the base of definition 1 the weighted finite element method is constructed. For that a quasi-uniform triangulation \( T^h \) of the \( \bar{\Omega} \) is performed and a special weighted basis functions are introduced.

By means of strains \( x = -1 + \frac{2i}{N}, \quad y = -1 + \frac{2j}{N}, \quad i,j = 0..N \) \( \bar{\Omega} \) is divided on squares and each of them by the diagonal is divided into two triangles \( K \) called finite elements, with vertices \( P_k \) \((k = 1,...,n^2)\) are called triangulation nodes. Denote \( \Omega^h = \bigcup_{K \in \tau^h} K \), \( h = \frac{2\sqrt{2}}{N} \) is a longest length of the finite elements sides. Denote \( P = \{P_k\}_{k=1}^{n^2} \) the set of all triangulation nodes among which \( \{P_k\}_{k=1}^{n^2} \) is the set of internal nodes and \( \{P_k\}_{k=n^2+1}^{n^2} \) is the set of boundary nodes.

For each \( P_k \in \{P_k\}_{k=1}^{n^2} \) a weight basis function \( \psi_k(x) = \rho^\gamma(x)\phi_k(x), \quad k = 1,...,n \) is introduced, where \( \phi_k(x) \) is a linear on each finite element and \( \phi_k(P_j) = \delta_{kj}, \quad k,j = 1,...,n \), \( \delta_{kj} \) denotes a Kronecker delta, \( \gamma \) is a real number.

Define the set \( V^h \) as a linear span of the basis functions \( \{\psi_k\}_{k=1}^{n^2}, \quad V^h = [V^h]^2 \). It the \( V^h \), a subset \( V^h = \{v \in V^h | v(P_i) \big|_{E_i = \Omega} = 0, i = 1,2 \} \) is separated.

**Definition 2.** A function \( u^h \in V^h \) is called an approximate \( R_\delta \)-generalized solution by the weighted finite element method to the problem (1),(2), if it satisfies boundary conditions (2) in nodes \( P_k \in \{P_k\}_{k=n^2+1}^{n^2} \) and for all \( v(x) \in V^h \) and \( v > \beta \) the integral identity

\[
a(u^h,v) = l(v^h)
\]

holds.

Components of approximate solution \( u^h \) will be found in the form

\[
u^h_{0,1} = \sum_{k=1}^{2n} d_{2k} \psi_k, \quad u^h_{0,2} = \sum_{k=1}^{2n} d_{2k} \psi_k, \quad d_j = \rho^{-\gamma}(P_{j+1}), c_j, \quad j = 1,...,2n.
\]

The unknowns \( d_j \) are defined from the system of linear equations \( a(u^h,v) = l(v) \), \( k = 1..2n \).

4. **Numerical experiment**

In the present section, the results of numerical experiment for one model problem are presented. As a solution we used the vector-function \( u = \frac{1}{E} \sqrt{\frac{r}{2\pi}} \left( 1 + \gamma \right) \left( \cos \left( \frac{\theta}{2} \right) \left( \xi - \cos(\theta) \right), \sin \left( \frac{\theta}{2} \right) \left( \xi - \cos(\theta) \right) \right) \),

where \( \gamma = \frac{\lambda}{\lambda + 2\mu}, \quad E = \frac{4\mu(\lambda + \mu)}{\lambda + 2\mu}, \quad \xi = 3 - 4\gamma \) (see [10]). Lamé parameters \( \lambda = 3.0 \) and \( \mu = 5.0 \).
Computations were carried out on meshes with different partition numbers \(N\). The errors of approximate generalized \((\nu = 0, \rho(x) = 1)\) and \(R_v\)-generalized solutions were compared in the norms of spaces \(W^1_2(\Omega), W^{1}_2(\Omega)\) and in the triangulation nodes. To do this, for the derived approximate generalized \(u^h\) and \(R_v\)-generalized \(u^h_v\) solutions a relative errors \(\eta = \frac{\|u^h - u^h_v\|_{W^1_2(\Omega)}}{\|u^h\|_{W^1_2(\Omega)}}\),

\[
\eta_v = \frac{\|u^h_v - u^h\|_{W^1_2(\Omega)}}{\|u^h\|_{W^1_2(\Omega)}},
\]

were computed, respectively. In the nodes \(P_i, i = 1, \ldots, n\) an absolute errors \(\delta_j = |u^h(P_i) - u^h_v(P_i)|\), \(\delta^*_j = |u^h_v(P_i) - u^h_v(P_j)|\) were calculated. A number and coordinates of the nodes \(P_i\), where the absolute errors are less than the limit value \(\bar{\Delta} = 10^{-5}\) were counted. Results of numerical experiments are presented in tables and figures. Optimal parameters \(\delta, \nu, \nu^*\) were derived by the software complex [22].

It Table 1 for the different \(N\) the values of \(\eta, \eta_v\) and the ratios between them on the adjacent meshes are presented.

**Table 1.** Dependence of the values of \(\eta, \eta_v\) and the ratios between them on the adjacent meshes.

| \(N\) | 32  | 64  | 128 | 256 | 512 | 1024 |
|------|-----|-----|-----|-----|-----|------|
| \(\eta\) | 1.130 \(\cdot 10^{-1}\) | 8.006 \(\cdot 10^{-2}\) | 5.666 \(\cdot 10^{-2}\) | 4.009 \(\cdot 10^{-2}\) | 2.835 \(\cdot 10^{-2}\) | 2.005 \(\cdot 10^{-2}\) |
| \(\eta_v\) | 1.024 \(\cdot 10^{-1}\) | 8.347 \(\cdot 10^{-2}\) | 4.003 \(\cdot 10^{-2}\) | 2.180 \(\cdot 10^{-2}\) | 1.836 \(\cdot 10^{-2}\) | 9.002 \(\cdot 10^{-3}\) |

On the Figure 2 a convergence rates of the approximate generalized (circled line) and \(R_v\)-generalized (rhombic line) solutions are presented in the logarithmic scales. Solid line designates convergence rate \(O(h)\).

**Figure 2.** Graph of \(\eta\) for the approximate generalized (circled line) and \(\eta_v\) for the approximate \(R_v\)-generalized (\(\delta = 0.015, \nu = 1.8, \nu^* = 0.0\)) solution (rhombic line).

In Table 2 and Table 3 we present a number of nodes \(P_i \in \{P_i\}_{i=1}^n\) in percentage of their total number, where the absolute errors \(\delta^*_j\) for approximate \(R_v\)-generalized solution and \(\delta_j\) for the approximate generalized solution, \(i = 1, \ldots, n\), \(j = 1, 2\) are less than the limit value \(\bar{\Delta} = 10^{-5}\). Distribution of the absolute error for component \(u^h_{i,j}\) of the approximate \(R_v\)-generalized solution and
for component $u_i^h$ of the approximate generalized solution for $N = 256$, $N = 512$ and $N = 1024$ are depicted on Fig. 3. Corresponding results for $u_{i,j}^h$, $u_{j}^h$ are depicted on Fig. 4.

**Remark.** During numerical experiment for the current problem, in contrast to the problems in works [17-21], the founded optimal value $\nu^* = 0.0$. Convergence rate $O(h)$ is achieved thanks to the introduction of $R_\nu$ -generalized solution.

**Table 2.** The number of nodes $P_i \in \{P_i\}_{i=1}^N$ in percentage of their total number, where the absolute errors $\delta_{ij}^\nu$ ( $n_{ij}^\nu$, approximate $R_\nu$ -generalized solution) and $\delta_{ij}$ ( $n_i$, approximate generalized solution), $i = 1, \ldots, n$, $j = 1, 2$ are less than the limit value $\Delta = 10^{-5}$.

| N   | 32     | 64     | 128    | 256    | 512    | 1024   |
|-----|--------|--------|--------|--------|--------|--------|
| $n_{ij}^\nu$ | 7.090% | 6.477% | 24.619%| 63.459%| 95.287%| 98.914%|
| $n_i$    | 6.875% | 15.976%| 28.826%| 47.428%| 73.642%| 95.205%|

![Distribution of the absolute error for component $u_{i,1}^h$ of the approximate $R_\nu$ -generalized solution, $\delta = 0.015$, $\nu = 1.8$, $\nu^* = 0.0$ (a) and for component $u_i^h$ of the approximate generalized solution (b).](image)

**Figure 3.** Distribution of the absolute error for component $u_{i,1}^h$ of the approximate $R_\nu$ -generalized solution, $\delta = 0.015$, $\nu = 1.8$, $\nu^* = 0.0$ (a) and for component $u_i^h$ of the approximate generalized solution (b).

**Table 3.** The number of nodes $P_i \in \{P_i\}_{i=1}^N$ in percentage of their total number, where the absolute errors $\delta_{ij}^\nu$ ( $n_{ij}^\nu$, approximate $R_\nu$ -generalized solution) and $\delta_{ij}$ ( $n_i$, approximate generalized solution), $i = 1, \ldots, n$, $j = 1, 2$ are less than the limit value $\Delta = 10^{-5}$.

| N   | 32     | 64     | 128    | 256    | 512    | 1024   |
|-----|--------|--------|--------|--------|--------|--------|
| $n_{ij}^\nu$ | 12.917%| 8.738% | 21.880%| 41.407%| 83.469%| 97.039%|
| $n_i$    | 12.698%| 16.053%| 24.265%| 34.856%| 47.955%| 63.193%|
Figure 4. Distribution of the absolute error for component $u^h_{v,2}$ of the approximate $R_v$-generalized solution, $\delta = 0.015$, $\nu = 1.8$, $\nu^* = 0.0$ (a) and for component $u^h_{2}$ of the approximate generalized solution (b).

Conclusion
From the presented numerical results one can make the following conclusions:

- an approximate $R_v$-generalized solution to the problem (1),(2) converges to the exact one with the rate $O(h)$ in the norm of the space $W^{1,\nu}_2(\Omega)$, whereas approximate generalized one converges with the rate $O(h^{1/2})$ in the norm of the space $W^1_2(\Omega)$;
- absolute error $\delta^v_{ij}$ of the approximate $R_v$-generalized solution in overwhelming majority of nodes is by one or two decimal orders less than absolute error $\delta_{ij}$ of the approximate generalized solution.

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