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Abstract: *The paper deals with the a-posteriori error analysis of mixed finite element methods for second order elliptic equations. It is shown that a reliable and efficient error estimator can be constructed using a postprocessed solution of the method. The analysis is performed in two different ways; under a saturation assumption and using a Helmholtz decomposition for vector fields.*

AMS subject classifications: 65N30

Keywords: mixed finite element methods, a-posteriori error estimates, post-processing.

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1 Introduction

We consider the mixed finite element approximation of second order elliptic equations with the Poisson problem as a model:

$$-\Delta u = f \quad \text{in } \Omega \subset \mathbb{R}^n, \tag{1.1}$$

$$u = 0 \quad \text{on } \partial\Omega. \tag{1.2}$$

The problem is written as the system

$$\boldsymbol{\sigma} - \nabla u = \mathbf{0}, \tag{1.3}$$

$$\operatorname{div} \boldsymbol{\sigma} + f = 0, \tag{1.4}$$

which is approximated with the

Mixed method. *Find* $(\boldsymbol{\sigma}_h, u_h) \in \boldsymbol{S}_h \times V_h \subset \boldsymbol{H}(\operatorname{div}:\Omega) \times L^2(\Omega)$ *such that*

$$(\boldsymbol{\sigma}_h, \boldsymbol{\tau}) + (\operatorname{div} \boldsymbol{\tau}, u_h) = 0 \quad \forall \boldsymbol{\tau} \in \boldsymbol{S}_h, \tag{1.5}$$

$$(\operatorname{div} \boldsymbol{\sigma}_h, v) + (f, v) = 0 \quad \forall v \in V_h. \tag{1.6}$$

In the method the polynomial used for approximating the flux $\boldsymbol{\sigma}$ is of higher degree than that used for the displacement u, which is counterintuitive in view of (1.3). As a consequence, the mixed method has to be carefully designed in order to satisfy the Babuška-Brezzi conditions, c.f. e.g. [7]. There are two ways of posing these conditions, both yielding the same a priori estimates. The more common one is to use the $\boldsymbol{H}(\operatorname{div}:\Omega)$ norm for the flux and the $L^2(\Omega)$ norm for the displacement. The other one is to use so called mesh dependent norms [2] which are close to the energy norm of the continuous problem.

The a posteriori error analysis of mixed methods has been performed in [9] and [4]. In [9] the estimate is for the $\boldsymbol{H}(\operatorname{div}:\Omega)$-norm. This is in a way unsatisfactory since the "div" part of the norm is trivially computable and also may dominate the error, see Remark 3.3 below. In [4] an estimate for the L^2-norm of the flux is derived but it is, however, not optimal. The reason for this is that the estimator includes the element residual in the constitutive relation (1.3). As the polynomial degree of approximation for the displacement is lower than that for the flux, it is clear that this residual is large.

The purpose of this paper is to point out a simple remedy to this. Since the work of Arnold and Brezzi [1] it is known that the mixed finite element solution can be locally postprocessed in order to obtain an improved displacement. Later other postprocessing has been proposed [5, 8, 6, 16, 15]. On each element the postprocessed displacement is of one degree higher than the flux, which is in accordance with (1.3). Hence, it is natural to use it in the a posteriori estimate. In this paper, we will focus on the postprocessing introduced in [16, 15]. In Section 2 we develop an a-priori error analysis by recognizing that the postprocessed output can be viewed as the direct solution of a suitable modified method. In Section 3 we introduce our estimator based on the postprocessed solution, and we prove its efficiency and reliability.

Throughout the paper we will use standard notations for Sobolev norms and seminorms. Moreover, we will denote with C a generic constant independent of the mesh parameter h, which may take different values in different occurrences.

2 A-priori estimates and postprocessing

In this section we will consider the mixed methods, their postprocessing and error analysis. We will also give the stability and error analysis by treating the method and the postprocessing as one method. This will be useful for the a posteriori analysis.

We will use standard notation used in connection with (mixed) FE methods. By $\mathcal{C}_h$ we denote the finite element partitioning and by Γ_h the collection of edges or faces of $\mathcal{C}_h$. The subspaces $(\boldsymbol{\sigma}_h, u_h) \in \boldsymbol{S}_h \times V_h \subset \boldsymbol{H}(\mathrm{div}:\Omega) \times L^2(\Omega)$ are piecewise polynomial spaces defined on $\mathcal{C}_h$. As examples we will consider the following families of elements.

- *RTN elements* – the triangular elements of Raviart-Thomas [14] and their tetrahedral counterparts of Nedelec [13];
- *BDM elements* – the triangular elements of Brezzi-Douglas-Marini [8] and their tetrahedral counterparts of Brezzi-Douglas-Duran-Fortin [6].

Accordingly, given an integer $k \geq 1$, we define:

$$\boldsymbol{S}_h^{RTN} = \{ \boldsymbol{\tau} \in \boldsymbol{H}(\mathrm{div}:\Omega) \,|\, \boldsymbol{\tau}|_K \in [P_{k-1}(K)]^n \oplus \boldsymbol{x}\tilde{P}_{k-1}(K) \ \forall K \in \mathcal{C}_h \} \tag{2.1}$$

$$\boldsymbol{S}_h^{BDM} = \{ \boldsymbol{\tau} \in \boldsymbol{H}(\mathrm{div}:\Omega) \,|\, \boldsymbol{\tau}|_K \in [P_k(K)]^n \ \forall K \in \mathcal{C}_h \} \tag{2.2}$$

$$V_h^{RTN} = V_h^{BDM} = \{ v \in L^2(\Omega) \,|\, v|_K \in P_{k-1}(K) \ \forall K \in \mathcal{C}_h \}, \tag{2.3}$$

where $\tilde{P}_{k-1}(K)$ denotes the homogeneous polynomials of degree $k-1$. For quadrilateral and hexahedral meshes there exist a wide choice of different alternatives, c.f. [7].

By defining the following bilinear form

$$\mathcal{B}(\boldsymbol{\varphi}, w; \boldsymbol{\tau}, v) = (\boldsymbol{\varphi}, \boldsymbol{\tau}) + (\mathrm{div}\, \boldsymbol{\tau}, w) + (\mathrm{div}\, \boldsymbol{\varphi}, v) \tag{2.4}$$

the mixed method can compactly be defined as:
Find $(\boldsymbol{\sigma}_h, u_h) \in \boldsymbol{S}_h \times V_h$ such that

$$\mathcal{B}(\boldsymbol{\sigma}_h, u_h; \boldsymbol{\tau}, v) + (f, v) = 0 \qquad \forall (\boldsymbol{\tau}, v) \in \boldsymbol{S}_h \times V_h. \tag{2.5}$$

For the displacement and the flux we will use the following norms:

$$\|v\|_{1,h}^2 = \sum_{K \in \mathcal{C}_h} \|\nabla v\|_{0,K}^2 + \sum_{E \in \Gamma_h} h_E^{-1} \|[\![v]\!]\|_{0,E}^2, \tag{2.6}$$

and

$$\|\boldsymbol{\tau}\|_{0,h}^2 = \|\boldsymbol{\tau}\|_0^2 + \sum_{E\in\Gamma_h} h_E \|\boldsymbol{\tau}\cdot\boldsymbol{n}\|_{0,E}^2, \tag{2.7}$$

where $\boldsymbol{n}$ is the unit normal to $E \in \Gamma_h$ and $[\![v]\!]$ is the jump in v along interior edges and v on edges on $\partial\Omega$. By an element by element partial integration we have

$$|(\operatorname{div}\boldsymbol{\tau}, v)| \le \|\boldsymbol{\tau}\|_{0,h}\|v\|_{1,h} \qquad \forall(\boldsymbol{\tau}, v) \in \boldsymbol{S}_h \times V_h. \tag{2.8}$$

In the FE subspace the norm for the flux is equivalent to the L^2 norm:

$$C_1\|\boldsymbol{\tau}\|_{0,h} \le \|\boldsymbol{\tau}\|_0 \le C_2\|\boldsymbol{\tau}\|_{0,h} \quad \forall\boldsymbol{\tau} \in \boldsymbol{S}_h. \tag{2.9}$$

Hence, it also holds

$$|(\operatorname{div}\boldsymbol{\tau}, v)| \le C\|\boldsymbol{\tau}\|_0\|v\|_{1,h} \qquad \forall(\boldsymbol{\tau}, v) \in \boldsymbol{S}_h \times V_h. \tag{2.10}$$

With this choice of norms the Babuška-Brezzi *stability condition* is

$$\sup_{\boldsymbol{\tau}\in\boldsymbol{S}_h} \frac{(\operatorname{div}\boldsymbol{\tau}, v)}{\|\boldsymbol{\tau}\|_0} \ge C\|v\|_{1,h} \quad \forall v \in V_h. \tag{2.11}$$

When dealing with the spaces $\boldsymbol{H}(\mathrm{div}:\Omega)$ and $L^2(\Omega)$, the corresponding Babuška-Brezzi condition is typically proved by means of a suitable *interpolation operator* $\boldsymbol{R}_h : \boldsymbol{H}(\mathrm{div}:\Omega) \cap L^s(\Omega) \to \boldsymbol{S}_h$, with $s > 2$, such that

$$(\operatorname{div}(\boldsymbol{\tau} - \boldsymbol{R}_h\boldsymbol{\tau}), v) = 0 \quad \forall v \in V_h, \tag{2.12}$$

which can be constructed by a careful choice of degrees of freedom for $\boldsymbol{S}_h$, cf. [14, 13, 8, 6]. The same techniques can, however, be used to prove the condition with our choice of norms. We should also point out that since $V_h^{RTN} = V_h^{BDM}$ and $\boldsymbol{S}_h^{RTN} \subset \boldsymbol{S}_h^{BDM}$ the stability estimate for BDM is a consequence of that for RTN.

In the sequel, we will assume that the method under consideration satisfies (2.11). As a consequence, the following full stability result holds.

Lemma 2.1 *There is a positive constant C such that*

$$\sup_{(\boldsymbol{\tau},v)\in\boldsymbol{S}_h\times V_h} \frac{\mathcal{B}(\boldsymbol{\varphi}, w; \boldsymbol{\tau}, v)}{\|\boldsymbol{\tau}\|_0 + \|v\|_{1,h}} \ge C\big(\|\boldsymbol{\varphi}\|_0 + \|w\|_{1,h}\big) \quad \forall(\boldsymbol{\varphi}, w) \in \boldsymbol{S}_h \times V_h. \tag{2.13}$$

This implies the uniqueness of the solution. In order to have an optimal estimate the additional *equilibrium property*

$$\operatorname{div}\boldsymbol{S}_h \subset V_h \tag{2.14}$$

is needed. When denoting by $P_h : L^2(\Omega) \to V_h$ the L^2-projection, this implies that

$$(\operatorname{div}\boldsymbol{\tau}, u - P_h u) = 0 \quad \forall\boldsymbol{\tau} \in \boldsymbol{S}_h. \tag{2.15}$$

The projection and interploation operators satisify the following *commuting property*:

$$\operatorname{div}\boldsymbol{R}_h = P_h\operatorname{div}. \tag{2.16}$$

Theorem 2.2 *There is a positive constant C such that*

$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_h\|_0 + \|P_h u - u_h\|_{1,h} \le C\|\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0. \tag{2.17}$$

Proof By Lemma 2.1 there is a pair $(\boldsymbol{\tau}, v) \in \boldsymbol{S}_h \times V_h$, with $\|\boldsymbol{\tau}\|_0 + \|v\|_{1,h} \le C$, such that

$$\|\boldsymbol{\sigma}_h - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0 + \|u_h - P_h u\|_{1,h} \le \mathcal{B}(\boldsymbol{\sigma}_h - \boldsymbol{R}_h\boldsymbol{\sigma}, u_h - P_h u; \boldsymbol{\tau}, v). \tag{2.18}$$

Next, (2.12), (2.15) and (2.16) give

$$\begin{aligned} &\mathcal{B}(\boldsymbol{\sigma}_h - \boldsymbol{R}_h\boldsymbol{\sigma}, u_h - P_h u; \boldsymbol{\tau}, v) \\ &= (\boldsymbol{\sigma}_h - \boldsymbol{R}_h\boldsymbol{\sigma}, \boldsymbol{\tau}) + (\operatorname{div}\boldsymbol{\tau}, u_h - P_h u) + (\operatorname{div}(\boldsymbol{\sigma}_h - \boldsymbol{R}_h\boldsymbol{\sigma}), v) \qquad (2.19)\\ &= (\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}, \boldsymbol{\tau}) \le \|\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0\|\boldsymbol{\tau}\|_0 \le C\|\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0. \end{aligned}$$

The assertion then follows from the triangle inequality. □

For the two examples of spaces this gives (assuming full regularity):

$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_h\|_0 + \|P_h u - u_h\|_{1,h} \le Ch^{k+1}|\boldsymbol{\sigma}|_{k+1} \qquad \text{for BDM}, \tag{2.20}$$

$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_h\|_0 + \|P_h u - u_h\|_{1,h} \le Ch^{k}|\boldsymbol{\sigma}|_{k} \qquad \text{for RTN}. \tag{2.21}$$

We note that these estimates contain a *superconvergence* result for $\|P_h u - u_h\|_{1,h}$. This, together with the fact that $\boldsymbol{\sigma}_h$ is a good approximation of ∇u, implies that an improved approximation for the displacement can be constructed by local *postprocessing*. Below we will consider the method introduced in [16, 15]. The postprocessed displacement is sought in a FE space $V_h^* \supset V_h$. For the two examples the spaces are

$$V_h^{*BDM} = \{\, v \in L^2(\Omega) \mid v|_K \in P_{k+1}(K)\ \forall K \in \mathcal{C}_h \,\}, \tag{2.22}$$

$$V_h^{*RTN} = \{\, v \in L^2(\Omega) \mid v|_K \in P_{k}(K)\ \forall K \in \mathcal{C}_h \,\}. \tag{2.23}$$

Postprocessing method. *Find $u_h^* \in V_h^*$ such that*

$$P_h u_h^* = u_h \tag{2.24}$$

and

$$(\nabla u_h^*, \nabla v)_K = (\boldsymbol{\sigma}_h, \nabla v)_K \quad \forall v \in (I - P_h)V_h^*|_K. \tag{2.25}$$

The error analysis of this postprocessing is done in [16, 15]. Here we proceed in a slightly different way by considering the method and the postprocessing as one method. To this end we define the bilinear form

$$\begin{aligned} \mathcal{B}_h(\boldsymbol{\varphi}, w^*; \boldsymbol{\tau}, v^*) = \ &(\boldsymbol{\varphi}, \boldsymbol{\tau}) + (\operatorname{div}\boldsymbol{\tau}, w^*) + (\operatorname{div}\boldsymbol{\varphi}, v^*) \\ &+ \sum_{K\in\mathcal{C}_h} (\nabla w^* - \boldsymbol{\varphi}, \nabla(I - P_h)v^*)_K. \end{aligned} \tag{2.26}$$

Then we have the following equivalence to the original problem.

Lemma 2.3 *Let $(\boldsymbol{\sigma}_h, u_h^*) \in \boldsymbol{S}_h \times V_h^*$ be the solution to the problem*

$$\mathcal{B}_h(\boldsymbol{\sigma}_h, u_h^*; \boldsymbol{\tau}, v^*) + (P_h f, v^*) = 0 \qquad \forall (\boldsymbol{\tau}, v^*) \in \boldsymbol{S}_h \times V_h^*, \tag{2.27}$$

and set $u_h = P_h u_h^* \in V_h$. Then $(\boldsymbol{\sigma}_h, u_h) \in \boldsymbol{S}_h \times V_h$ coincides with the solution of (1.5)–(1.6)*. Conversely, let $(\boldsymbol{\sigma}_h, u_h) \in \boldsymbol{S}_h \times V_h$ be the solution of* (1.5)–(1.6)*, and let $u_h^* \in V_h^*$ be the postprocessed displacement defined by* (2.24)–(2.25)*. Then $(\boldsymbol{\sigma}_h, u_h^*) \in \boldsymbol{S}_h \times V_h^*$ is the solution to* (2.27)*.*

Proof Testing by $(\boldsymbol{\tau}, 0) \in \boldsymbol{S}_h \times V_h^*$ in (2.27) gives

$$(\boldsymbol{\sigma}_h, \boldsymbol{\tau}) + (\operatorname{div} \boldsymbol{\tau}, u_h^*) = 0 \quad \forall \boldsymbol{\tau} \in \boldsymbol{S}_h. \tag{2.28}$$

The equilibrium property (2.14) implies

$$(\operatorname{div} \boldsymbol{\tau}, u_h^*) = (\operatorname{div} \boldsymbol{\tau}, u_h). \tag{2.29}$$

Hence, (1.5) is satisfied. Next, for a generic $v^* \in V_h^*$ set $v = P_h v^* \in V_h$ and observe that $V_h = P_h(V_h^*)$. Testing in (2.27) with $(\mathbf{0}, v)$, and using the fact that $(P_h f, v) = (f, v)$, we obtain

$$(\operatorname{div} \boldsymbol{\sigma}_h, v) + (f, v) = 0 \quad \forall v \in V_h, \tag{2.30}$$

i.e. the equation (1.6). Conversely, let $(\boldsymbol{\sigma}_h, u_h) \in \boldsymbol{S}_h \times V_h$ be the solution of (1.5)–(1.6), and let $u_h^* \in V_h^*$ be defined by (2.24)–(2.25). Splitting a generic $v^* \in V_h^*$ as $v^* = P_h v^* + (I - P_h) v^*$ we have

$$\begin{aligned}
\mathcal{B}_h(\boldsymbol{\sigma}_h, u_h^*; \boldsymbol{\tau}, v^*) &= \mathcal{B}_h(\boldsymbol{\sigma}_h, u_h^*; \boldsymbol{\tau}, P_h v^*) + \mathcal{B}_h(\boldsymbol{\sigma}_h, u_h^*; \boldsymbol{\tau}, (I - P_h) v^*) \\
&= (\boldsymbol{\sigma}_h, \boldsymbol{\tau}) + (\operatorname{div} \boldsymbol{\tau}, u_h^*) + (\operatorname{div} \boldsymbol{\sigma}_h, P_h v^*) + \sum_{K \in \mathcal{C}_h} (\nabla u_h^* - \boldsymbol{\sigma}_h, \nabla (I - P_h) P_h v^*)_K \\
&\quad + (\operatorname{div} \boldsymbol{\sigma}_h, (I - P_h) v^*) + \sum_{K \in \mathcal{C}_h} (\nabla u_h^* - \boldsymbol{\sigma}_h, \nabla (I - P_h)(I - P_h) v^*)_K \\
&= (\boldsymbol{\sigma}_h, \boldsymbol{\tau}) + (\operatorname{div} \boldsymbol{\tau}, u_h) - (P_h f, P_h v^*) = -(P_h f, v^*) \qquad \forall (\boldsymbol{\tau}, v^*) \in \boldsymbol{S}_h \times V_h^*.
\end{aligned} \tag{2.31}$$

Therefore, $(\boldsymbol{\sigma}_h, u_h^*) \in \boldsymbol{S}_h \times V_h^*$ solves (2.27). □

Next, we prove the stability.

Lemma 2.4 *There is a positive constant constant C such that*

$$\sup_{(\boldsymbol{\tau}, v^*) \in \boldsymbol{S}_h \times V_h^*} \frac{\mathcal{B}_h(\boldsymbol{\varphi}, w^*; \boldsymbol{\tau}, v^*)}{\|\boldsymbol{\tau}\|_0 + \|v^*\|_{1,h}} \geq C \big(\|\boldsymbol{\varphi}\|_0 + \|w^*\|_{1,h} \big) \quad \forall (\boldsymbol{\varphi}, w^*) \in \boldsymbol{S}_h \times V_h^*. \tag{2.32}$$

*Proof*Let $(\boldsymbol{\varphi}, w^*) \in \boldsymbol{S}_h \times V_h^*$ be arbitrary. By choosing $v^* = v \in V_h$ and using the equilibrium condition (2.14) we then get

$$\begin{aligned}
\mathcal{B}_h(\boldsymbol{\varphi}, w^*; \boldsymbol{\tau}, v) &= (\boldsymbol{\varphi}, \boldsymbol{\tau}) + (\operatorname{div} \boldsymbol{\tau}, w^*) + (\operatorname{div} \boldsymbol{\varphi}, v) \\
&= (\boldsymbol{\varphi}, \boldsymbol{\tau}) + (\operatorname{div} \boldsymbol{\tau}, P_h w^*) + (\operatorname{div} \boldsymbol{\varphi}, v) \\
&= \mathcal{B}(\boldsymbol{\varphi}, P_h w^*; \boldsymbol{\tau}, v),
\end{aligned} \tag{2.33}$$

Hence, the stability of Lemma 2.1 implies that we can choose $(\boldsymbol{\tau}, v)$ such that

$$\mathcal{B}_h(\boldsymbol{\varphi}, w^*; \boldsymbol{\tau}, v) \geq \big(\|\boldsymbol{\varphi}\|_0^2 + \|P_h w^*\|_{1,h}^2\big) \tag{2.34}$$

and

$$\|\boldsymbol{\tau}\|_0 + \|v\|_{1,h} \leq C_1\big(\|\boldsymbol{\varphi}\|_0 + \|P_h w^*\|_{1,h}\big). \tag{2.35}$$

Next, (2.10) and Young's inequality give

$$\begin{aligned}
&\mathcal{B}_h(\boldsymbol{\varphi}, w^*; \mathbf{0}, (I-P_h)w^*) \\
&= (\operatorname{div} \boldsymbol{\varphi}, (I-P_h)w^*) + \sum_{K\in\mathcal{C}_h} (\nabla w^* - \boldsymbol{\varphi}, \nabla (I-P_h)w^*)_K \\
&\geq -C_2\|\boldsymbol{\varphi}\|_0 \|(I-P_h)w^*\|_{1,h} - \|(I-P_h)w^*\|_{1,h}\|P_h w^*\|_{1,h} \\
&\qquad + \sum_{K\in\mathcal{C}_h} \|\nabla(I-P_h)w^*\|_{0,K}^2 \\
&\geq -C_2^2\|\boldsymbol{\varphi}\|_0^2 - \|P_h w^*\|_{1,h}^2 + \frac{1}{2}\sum_{K\in\mathcal{C}_h} \|\nabla(I-P_h)w^*\|_{0,K}^2.
\end{aligned} \tag{2.36}$$

Combining (2.34) and (2.36), with $\delta = 1/2(C_2^2+1)$, we get

$$\begin{aligned}
&\mathcal{B}_h(\boldsymbol{\varphi}, w^*; \boldsymbol{\tau}, v + \delta(I-P_h)w^*) \\
&\geq \frac{1}{2}\Big(\|\boldsymbol{\varphi}\|_0^2 + \|P_h w^*\|_{1,h}^2 + \delta \sum_{K\in\mathcal{C}_h} \|\nabla(I-P_h)w^*\|_{0,K}^2\Big).
\end{aligned} \tag{2.37}$$

By scaling we have

$$\|P_h w^*\|_{1,h}^2 + \delta \sum_{K\in\mathcal{C}_h} \|\nabla(I-P_h)w^*\|_{0,K}^2 \geq C_3\|w^*\|_{1,h}^2. \tag{2.38}$$

From (2.35) and (2.38) we have

$$\|\boldsymbol{\tau}\|_0 + \|v + \delta(I-P_h)w^*\|_{1,h} \leq C_4\big(\|\boldsymbol{\varphi}\|_0 + \|w^*\|_{1,h}\big) \tag{2.39}$$

and the asserted estimate is proved. □

Theorem 2.5 *The following a priori error estimate holds*

$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_h\|_0 + \|u - u_h^*\|_{1,h} \leq C\big(\|\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0 + \inf_{v^*\in V_h^*} \|u - v^*\|_{1,h}\big).$$

Proof From Lemma 2.4 it follows that there is $(\boldsymbol{\varphi}, w^*) \in \boldsymbol{S}_h \times V_h^*$, with $\|\boldsymbol{\varphi}\|_0 + \|w^*\|_{1,h} \leq C$, such that

$$\big(\|\boldsymbol{\sigma}_h - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0 + \|u_h^* - v^*\|_{1,h}\big) \leq \mathcal{B}_h(\boldsymbol{\sigma}_h - \boldsymbol{R}_h\boldsymbol{\sigma}, u_h^* - v^*; \boldsymbol{\varphi}, w^*). \tag{2.41}$$

Next, from the definition of $\mathcal{B}_h$ and the equations (1.3)–(1.4) it follows that

$$\mathcal{B}_h(\boldsymbol{\sigma}, u; \boldsymbol{\varphi}, w^*) + (f, w^*) = 0. \tag{2.42}$$

Hence it holds

$$\mathcal{B}_h(\boldsymbol{\sigma}_h - \boldsymbol{R}_h\boldsymbol{\sigma}, u_h^* - v^*; \boldsymbol{\varphi}, w^*) \qquad (2.43)$$
$$= \mathcal{B}_h(\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}, u - v^*; \boldsymbol{\varphi}, w^*) + (f - P_h f, w^*).$$

Writing out the right hand side we have

$$\mathcal{B}_h(\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}, u - v^*; \boldsymbol{\varphi}, w^*) + (f - P_h f, w^*) \qquad (2.44)$$
$$= (\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}, \boldsymbol{\varphi}) + (\operatorname{div}\boldsymbol{\varphi}, u - v^*) + (\operatorname{div}(\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}), w^*)$$
$$+ \sum_{K\in\mathcal{C}_h} (\nabla(u - v^*) - (\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}), \nabla(I - P_h)w^*)_K + (f - P_h f, w^*).$$

The commuting property (2.16) gives

$$(\operatorname{div}(\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}), w^*) = -(f - P_h f, w^*). \qquad (2.45)$$

Hence, the third and the last term on the right hand side of (2.44) cancel. The other terms are directly estimated

$$(\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}, \boldsymbol{\varphi}) \le \|\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0 \|\boldsymbol{\varphi}\|_0 \le C\|\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0, \qquad (2.46)$$
$$(\operatorname{div}\boldsymbol{\varphi}, u - v^*) \le C\|\boldsymbol{\varphi}\|_0 \|u - v^*\|_{1,h} \le C\|u - v^*\|_{1,h} \qquad (2.47)$$

and

$$\sum_{K\in\mathcal{C}_h} (\nabla(u - v^*) - (\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}), \nabla(I - P_h)w^*)_K \qquad (2.48)$$
$$\le C\big(\|u - v^*\|_{1,h} + \|\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0\big)\|w^*\|_{1,h}$$
$$\le C\big(\|u - v^*\|_{1,h} + \|\boldsymbol{\sigma} - \boldsymbol{R}_h\boldsymbol{\sigma}\|_0\big).$$

The assertion then follows by collecting the above estimate and using the triangle inequality. □

For the example methods we obtain the estimates (with the assumption of a sufficiently smooth solution).

Corollary 2.6 *There are positive constants C such that*

$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_h\|_0 + \|u - u_h^*\|_{1,h} \le Ch^{k+1}|u|_{k+2} \qquad \text{for BDM}, \qquad (2.49)$$
$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_h\|_0 + \|u - u_h^*\|_{1,h} \le Ch^{k}|u|_{k+1} \qquad \text{for RTN}. \qquad (2.50)$$

3 A-posteriori estimates

We define the following local error indicators on the elements

$$\eta_{1,K} = \|\nabla u_h^* - \boldsymbol{\sigma}_h\|_{0,K}, \quad \eta_{2,K} = h_K\|f - P_h f\|_{0,K}, \qquad (3.1)$$

and on the edges

$$\eta_E = h_E^{-1/2}\|[\![u_h^*]\!]\|_{0,E}. \qquad (3.2)$$

Using these quantities, the global estimator is

$$\eta = \Big(\sum_{K\in\mathcal{C}_h} \big(\eta_{1,K}^2 + \eta_{2,K}^2\big) + \sum_{E\in\Gamma_h} \eta_E^2 \Big)^{1/2}. \tag{3.3}$$

The efficiency of the estimator is given by the following lower bounds, which directly follow from (1.3) using the triangle inequality, and from (3.2) noting that $[\![u]\!] = 0$ on each edge E.

Theorem 3.1 *It holds*

$$\begin{aligned} \eta_{1,K} &\le \|\nabla(u-u_h^*)\|_{0,K} + \|\boldsymbol{\sigma}-\boldsymbol{\sigma}_h\|_{0,K}, \\ \eta_E &= h_E^{-1/2}\|[\![u-u_h^*]\!]\|_{0,E}. \end{aligned} \tag{3.4}$$

As far as the estimator reliability is concerned, below we will use two different techniques to prove the following upper bound

Theorem 3.2 *There exists a positive constant C such that*

$$\|\boldsymbol{\sigma}-\boldsymbol{\sigma}_h\|_0 + \|u-u_h^*\|_{1,h} \le C\eta. \tag{3.5}$$

The first technique to prove the upper bound is based on the following saturation assumption. We let $\mathcal{C}_{h/2}$ be the mesh obtained from $\mathcal{C}_h$ by refined each element into 2^n $(n = 2, 3)$ elements. For clarity all variables in the spaces defined on $\mathcal{C}_h$ will be equipped with the subscript h whereas $h/2$ will be used for those defined on $\mathcal{C}_{h/2}$. Accordingly, we let $(\boldsymbol{\sigma}_{h/2}, u_{h/2}^*) \in \boldsymbol{S}_{h/2}\times V_{h/2}^*$ be the solution to

$$\mathcal{B}_{h/2}(\boldsymbol{\sigma}_{h/2}, u_{h/2}^*; \boldsymbol{\tau}_{h/2}, v_{h/2}^*) + (P_{h/2}f, v_{h/2}^*) = 0 \quad \forall(\boldsymbol{\tau}_{h/2}, v_{h/2}^*) \in \boldsymbol{S}_{h/2}\times V_{h/2}^*. \tag{3.6}$$

As already done in [4], we make the following assumption for the solutions of (2.27) and (3.6).

Saturation assumption. *There exists a positive constant $\beta < 1$ such that*

$$\|\boldsymbol{\sigma}-\boldsymbol{\sigma}_{h/2}\|_0 + \|u-u_{h/2}^*\|_{1,h/2} \le \beta\big(\|\boldsymbol{\sigma}-\boldsymbol{\sigma}_h\|_0 + \|u-u_h^*\|_{1,h}\big). \tag{3.7}$$

Using the triangle inequality this gives

$$\|\boldsymbol{\sigma}-\boldsymbol{\sigma}_h\|_0 + \|u-u_h^*\|_{1,h} \le \frac{1}{1-\beta}\big(\|\boldsymbol{\sigma}_{h/2}-\boldsymbol{\sigma}_h\|_0 + \|u_{h/2}^*-u_h^*\|_{1,h/2}\big). \tag{3.8}$$

Proof of Theorem 3.2 using the saturation assumption. By (3.8) it is sufficient to prove the following bound

$$\|\boldsymbol{\sigma}_{h/2}-\boldsymbol{\sigma}_h\|_0 + \|u_{h/2}^*-u_h^*\|_{1,h/2} \le C\eta. \tag{3.9}$$

By Lemma 2.4 applied to the finer mesh $\mathcal{C}_{h/2}$, there is $(\boldsymbol{\tau}_{h/2}, v_{h/2}^*) \in \boldsymbol{S}_{h/2}\times V_{h/2}^*$, with $\|\boldsymbol{\tau}_{h/2}\|_0 + \|v_{h/2}^*\|_{1,h/2} \le C$, such that

$$\begin{aligned} &\big(\|\boldsymbol{\sigma}_h-\boldsymbol{\sigma}_{h/2}\|_0 + \|u_h^*-u_{h/2}^*\|_{1,h/2}\big) \\ &\quad \le \mathcal{B}_{h/2}(\boldsymbol{\sigma}_h-\boldsymbol{\sigma}_{h/2}, u_h^*-u_{h/2}^*; \boldsymbol{\tau}_{h/2}, v_{h/2}^*). \end{aligned} \tag{3.10}$$

Using the fact that

$$(\boldsymbol{\sigma}_{h/2}, \boldsymbol{\tau}_{h/2}) + (\operatorname{div} \boldsymbol{\tau}_{h/2}, u^*_{h/2}) = 0 \tag{3.11}$$

we have

$$\begin{aligned}
&\mathcal{B}_{h/2}(\boldsymbol{\sigma}_h - \boldsymbol{\sigma}_{h/2}, u^*_h - u^*_{h/2}; \boldsymbol{\tau}_{h/2}, v^*_{h/2}) \\
&\quad = (\boldsymbol{\sigma}_h - \boldsymbol{\sigma}_{h/2}, \boldsymbol{\tau}_{h/2}) + (\operatorname{div} \boldsymbol{\tau}_{h/2}, u^*_h - u^*_{h/2}) + (\operatorname{div}(\boldsymbol{\sigma}_h - \boldsymbol{\sigma}_{h/2}), v^*_{h/2}) \\
&\qquad + \sum_{K \in \mathcal{C}_{h/2}} (\nabla(u^*_h - u^*_{h/2}) - (\boldsymbol{\sigma}_h - \boldsymbol{\sigma}_{h/2}), \nabla(I - P_h) v^*_{h/2})_K \qquad (3.12)\\
&\quad = (\boldsymbol{\sigma}_h, \boldsymbol{\tau}_{h/2}) + (\operatorname{div} \boldsymbol{\tau}_{h/2}, u^*_h) + (\operatorname{div}(\boldsymbol{\sigma}_h - \boldsymbol{\sigma}_{h/2}), v^*_{h/2}) \\
&\qquad + \sum_{K \in \mathcal{C}_{h/2}} (\nabla u^*_h - \boldsymbol{\sigma}_h, \nabla(I - P_h) v^*_{h/2})_K,
\end{aligned}$$

Using (2.9) and (3.1)–(3.3), we obtain

$$\begin{aligned}
&(\boldsymbol{\sigma}_h, \boldsymbol{\tau}_{h/2}) + (\operatorname{div} \boldsymbol{\tau}_{h/2}, u^*_h) \\
&\quad = \sum_{K \in \mathcal{C}_h} (\boldsymbol{\sigma}_h - \nabla u^*_h, \boldsymbol{\tau}_{h/2})_K + \sum_{E \in \Gamma_h} \langle \boldsymbol{\tau}_{h/2} \cdot \boldsymbol{n}, [\![u^*_h]\!] \rangle_E \\
&\quad \le \sum_{K \in \mathcal{C}_h} \|\boldsymbol{\sigma}_h - \nabla u^*_h\|_{0,K} \|\boldsymbol{\tau}_{h/2}\|_{0,K} + \sum_{E \in \Gamma_h} \|\boldsymbol{\tau}_{h/2} \cdot \boldsymbol{n}\|_{0,E} \|[\![u^*_h]\!]\|_{0,E} \qquad (3.13)\\
&\quad \le \eta \|\boldsymbol{\tau}_{h/2}\|_{0,h} \le \eta C \|\boldsymbol{\tau}_{h/2}\|_0 \le C\eta.
\end{aligned}$$

Similarly for the last term in (3.12) we get

$$\begin{aligned}
&\sum_{K \in \mathcal{C}_{h/2}} (\nabla u^*_h - \boldsymbol{\sigma}_h, \nabla(I - P_h) v^*_{h/2})_K \le C\eta \|(I - P_h) v^*_{h/2}\|_{1,h/2} \qquad (3.14)\\
&\qquad \le C\eta \|v^*_{h/2}\|_{1,h/2} \le C\eta.
\end{aligned}$$

When estimating the term $(\operatorname{div}(\boldsymbol{\sigma}_h - \boldsymbol{\sigma}_{h/2}), v^*_{h/2})$ in (3.12) we use that

$$(\operatorname{div} \boldsymbol{\sigma}_{h/2}, v^*_{h/2}) + (f, v^*_{h/2}) = 0,$$

$\operatorname{div} \boldsymbol{\sigma}_h = -P_h f$ and that P_h is the L^2-projection operator. Therefore, we have

$$\begin{aligned}
&(\operatorname{div}(\boldsymbol{\sigma}_h - \boldsymbol{\sigma}_{h/2}), v^*_{h/2}) = (f - P_h f, v^*_{h/2}) \\
&\quad = (f - P_h f, v^*_{h/2} - P_h v^*_{h/2}) \\
&\quad \le \|f - P_h f\|_0 \|v^*_{h/2} - P_h v^*_{h/2}\|_0 \qquad (3.15)\\
&\quad \le C\Big(\sum_{K \in \mathcal{C}_h} h_K^2 \|f - P_h f\|^2_{0,K}\Big)^{1/2} \|v^*_{h/2}\|_{1,h/2} \\
&\quad \le C\Big(\sum_{K \in \mathcal{C}_h} h_K^2 \|f - P_h f\|^2_{0,K}\Big)^{1/2} \le C\eta.
\end{aligned}$$

Here, we have used the interpolation estimates

$$\|v^*_{h/2} - P_h v^*_{h/2}\|_{0,K} \le C h_K |v^*_{h/2}|_{1,h/2,K}, \quad \forall K \in \mathcal{C}_h, \tag{3.16}$$

where

$$|v^*_{h/2}|^2_{1,h/2,K} = \sum_{K_i} \|\nabla v^*_{h/2}\|^2_{0,K_i} + \sum_{E_i} h^{-1}_{E_i} \|[\![v^*_{h/2}]\!]\|^2_{0,E_i} \tag{3.17}$$

and $K_i \subset K$ are the elements of $\mathcal{C}_{h/2}$ and E_i are the edges of $\Gamma_{h/2}$ lying in the interior of K. These are easily proved by standard scaling arguments, cf. [4, Lemma 3.1]. By collecting the estimates (3.13)–(3.15), from (3.12) we get

$$\mathcal{B}_{h/2}(\boldsymbol{\sigma}_h - \boldsymbol{\sigma}_{h/2}, u^*_h - u^*_{h/2}; \boldsymbol{\tau}_{h/2}, v^*_{h/2}) \le C\eta. \tag{3.18}$$

The assertion now follows from (3.10). □

We have presented the above proof since this is rather general and can be used for other problems as well. In [12] we use it for a plate bending method.

Next, let us give the other proof not relying on the saturation assumption.

Proof of Theorem 3.2 using a Helmholtz decomposition. We use the techniques of [10] and [9]. For simplicity we consider the two dimensional case $\Omega \subset \mathbb{R}^2$. We first notice that

$$||\boldsymbol{\sigma} - \boldsymbol{\sigma}_h||_0 = \sup_{\boldsymbol{\varphi} \in \boldsymbol{L}^2(\Omega)} \frac{(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h, \boldsymbol{\varphi})}{||\boldsymbol{\varphi}||_0}. \tag{3.19}$$

For a generic $\boldsymbol{\varphi} \in \boldsymbol{L}^2(\Omega)$, we consider the $\boldsymbol{L}^2$-orthogonal Helmholtz decomposition (see, e.g. [11]):

$$\boldsymbol{\varphi} = \nabla\psi + \mathbf{curl}\, q, \qquad \psi \in H^1_0(\Omega), \quad q \in H^1(\Omega)/\mathbb{R}, \tag{3.20}$$

with

$$||\boldsymbol{\varphi}||_0 = \Big(||\nabla\psi||^2_0 + ||\mathbf{curl}\, q||^2_0 \Big)^{1/2}. \tag{3.21}$$

Therefore, from (3.19)–(3.21) we see that it holds

$$||\boldsymbol{\sigma} - \boldsymbol{\sigma}_h||_0 \le \sup_{\psi \in H^1_0(\Omega)} \frac{(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h, \nabla\psi)}{|\psi|_1} + \sup_{q \in H^1(\Omega)/\mathbb{R}} \frac{(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h, \mathbf{curl}\, q)}{|q|_1}. \tag{3.22}$$

Given $\psi \in H^1_0(\Omega)$, from (1.4) and (1.6) it follows that

$$\big(\mathrm{div}\,(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h), P_h\psi\big) = 0. \tag{3.23}$$

Hence, we have

$$\begin{aligned}
(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h, \nabla\psi) &= -\,(\mathrm{div}\,(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h), \psi) \\
&= -\,(\mathrm{div}\,(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h), \psi - P_h\psi) \\
&\le C\Big(\sum_{K \in \mathcal{C}_h} h^2_K ||\mathrm{div}\,(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h)||^2_{0,K} \Big)^{1/2} |\psi|_1 \\
&\le C\Big(\sum_{K \in \mathcal{C}_h} h^2_K ||f - P_h f||^2_{0,K} \Big)^{1/2} |\psi|_1.
\end{aligned} \tag{3.24}$$

As a consequence, we get (cf. (3.1))

$$\sup_{\psi\in H_0^1(\Omega)} \frac{(\boldsymbol{\sigma}-\boldsymbol{\sigma}_h,\nabla\psi)}{|\psi|_1} \le C\Big(\sum_{K\in\mathcal{C}_h} h_K^2||f-P_hf||_{0,K}^2\Big)^{1/2} = C\Big(\sum_{K\in\mathcal{C}_h}\eta_{2,K}^2\Big)^{1/2}. \tag{3.25}$$

To continue, let I_hq be the Cleḿent interpolant of q in the space of continuous piecewise linear functions (see [3], for instance) satisfying

$$\|q-I_hq\|_1 + \Big(\sum_{E\in\Gamma_h} h_E^{-1}||q-I_hq||_{0,E}^2\Big)^{1/2} \le C|q|_1. \tag{3.26}$$

Noting that $\mathbf{curl}\, I_hq\in \boldsymbol{S}_h$, and $\operatorname{div}\mathbf{curl}\, I_hq=0$, from (1.3) and (1.5) we get

$$(\boldsymbol{\sigma}-\boldsymbol{\sigma}_h,\mathbf{curl}\, I_hq)=0. \tag{3.27}$$

Therefore, using (3.26), one has

$$\begin{aligned}(\boldsymbol{\sigma}-\boldsymbol{\sigma}_h,\mathbf{curl}\, q) &= \big(\boldsymbol{\sigma}-\boldsymbol{\sigma}_h,\mathbf{curl}(q-I_hq)\big)\\ &=\big(\nabla u-\boldsymbol{\sigma}_h,\mathbf{curl}(q-I_hq)\big) = -\big(\boldsymbol{\sigma}_h,\mathbf{curl}(q-I_hq)\big)\\ &=-\sum_{K\in\mathcal{C}_h}\big(\boldsymbol{\sigma}_h-\nabla u_h^*,\mathbf{curl}(q-I_hq)\big)_K+\sum_{K\in\mathcal{C}_h}\big(\nabla u_h^*,\mathbf{curl}(q-I_hq)\big)_K\\ &\le C\Big(\sum_{K\in\mathcal{C}_h}||\boldsymbol{\sigma}_h-\nabla u_h^*||_{0,K}^2\Big)^{1/2}|q|_1+\sum_{K\in\mathcal{C}_h}\big(\nabla u_h^*,\mathbf{curl}(q-I_hq)\big)_K.\end{aligned} \tag{3.28}$$

Furthermore, an integration by parts and standard arguments and (3.26) give

$$\begin{aligned}\sum_{K\in\mathcal{C}_h}\big(\nabla u_h^*,\mathbf{curl}(q-I_hq)\big)_K &= -\sum_{K\in\mathcal{C}_h}\langle\nabla u_h^*\cdot\boldsymbol{t}\,,q-I_hq\rangle_{\partial K}\\ &=-\sum_{E\in\Gamma_h}\langle[\![\nabla u_h^*\cdot\boldsymbol{t}]\!],q-I_hq\rangle_E\\ &\le\Big(\sum_{E\in\Gamma_h}h_E||[\![\nabla u_h^*\cdot\boldsymbol{t}]\!]||_{0,E}^2\Big)^{1/2}\Big(\sum_{E\in\Gamma_h}h_E^{-1}||q-I_hq||_{0,E}^2\Big)^{1/2}\\ &\le C\Big(\sum_{E\in\Gamma_h}h_E^{-1}||[\![u_h^*]\!]||_{0,E}^2\Big)^{1/2}|q|_1.\end{aligned} \tag{3.29}$$

From (3.28) and (3.29) we obtain (see (3.1) and (3.2))

$$\begin{aligned}\sup_{q\in H^1(\Omega)/\mathbb{R}}\frac{(\boldsymbol{\sigma}-\boldsymbol{\sigma}_h,\mathbf{curl}\, q)}{|q|_1} &\le C\Big(\sum_{K\in\mathcal{C}_h}||\boldsymbol{\sigma}_h-\nabla u_h^*||_{0,K}^2+\sum_{E\in\Gamma_h}h_E^{-1}||[\![u_h^*]\!]||_{0,E}^2\Big)^{1/2}\\ &=C\Big(\sum_{K\in\mathcal{C}_h}\eta_{1,K}^2+\sum_{E\in\Gamma_h}\eta_E^2\Big)^{1/2}.\end{aligned} \tag{3.30}$$

Using (3.25) and (3.30) we deduce

$$||\boldsymbol{\sigma} - \boldsymbol{\sigma}_h||_0 \leq C\Big(\sum_{K\in\mathcal{C}_h} (\eta_{1,K}^2 + \eta_{2,K}^2) + \sum_{E\in\Gamma_h} \eta_E^2 \Big)^{1/2}. \tag{3.31}$$

We now estimate the term $||u - u_h^*||_{1,h}$. We first recall that

$$||u - u_h^*||_{1,h} = \Big(\sum_{K\in\mathcal{C}_h} \|\nabla(u-u_h^*)\|_{0,K}^2 + \sum_{E\in\Gamma_h} h_E^{-1}\|[\![u-u_h^*]\!]\|_{0,E}^2 \Big)^{1/2} \tag{3.32}$$

and we notice that (cf. (3.2))

$$\Big(\sum_{E\in\Gamma_h} h_E^{-1}\|[\![u-u_h^*]\!]\|_{0,E}^2 \Big)^{1/2} = \Big(\sum_{E\in\Gamma_h} h_E^{-1}\|[\![u_h^*]\!]\|_{0,E}^2 \Big)^{1/2} = \Big(\sum_{E\in\Gamma_h} \eta_E^2 \Big)^{1/2}. \tag{3.33}$$

We have

$$\begin{aligned}
\|\nabla(u-u_h^*)\|_{0,K}^2 &= \big(\nabla u - \nabla u_h^*\,, \nabla(u-u_h^*)\big)_K = \big(\boldsymbol{\sigma} - \nabla u_h^*\,, \nabla(u-u_h^*)\big)_K \\
&= \big(\boldsymbol{\sigma} - \boldsymbol{\sigma}_h, \nabla(u-u_h^*)\big)_K + \big(\boldsymbol{\sigma}_h - \nabla u_h^*\,, \nabla(u-u_h^*)\big)_K \\
&\leq \Big(||\boldsymbol{\sigma} - \boldsymbol{\sigma}_h||_{0,K} + ||\boldsymbol{\sigma}_h - \nabla u_h^*||_{0,K}\Big)||\nabla(u-u_h^*)||_{0,K},
\end{aligned} \tag{3.34}$$

by which we obtain

$$\|\nabla(u-u_h^*)\|_{0,K} \leq ||\boldsymbol{\sigma} - \boldsymbol{\sigma}_h||_{0,K} + ||\boldsymbol{\sigma}_h - \nabla u_h^*||_{0,K}. \tag{3.35}$$

Hence we infer

$$\Big(\sum_{K\in\mathcal{C}_h} ||\nabla(u-u_h^*)||_{0,K}^2 \Big)^{1/2} \leq ||\boldsymbol{\sigma} - \boldsymbol{\sigma}_h||_0 + \Big(\sum_{K\in\mathcal{C}_h} ||\boldsymbol{\sigma}_h - \nabla u_h^*||_{0,K}^2 \Big)^{1/2}. \tag{3.36}$$

Using (3.31) and recalling (3.1), from (3.36) we get

$$\Big(\sum_{K\in\mathcal{C}_h} ||\nabla(u-u_h^*)||_{0,K}^2 \Big)^{1/2} \leq C\Big(\sum_{K\in\mathcal{C}_h} (\eta_{1,K}^2 + \eta_{2,K}^2) + \sum_{E\in\Gamma_h} \eta_E^2 \Big)^{1/2}. \tag{3.37}$$

Therefore, joining (3.33) and (3.37) we obtain

$$||u - u_h^*||_{1,h} \leq C\Big(\sum_{K\in\mathcal{C}_h} (\eta_{1,K}^2 + \eta_{2,K}^2) + \sum_{E\in\Gamma_h} \eta_E^2 \Big)^{1/2}. \tag{3.38}$$

From (3.31) and (3.38) we finally deduce (see (3.3))

$$||\boldsymbol{\sigma} - \boldsymbol{\sigma}_h||_0 + ||u - u_h^*||_{1,h} \leq C\Big(\sum_{K\in\mathcal{C}_h} (\eta_{1,K}^2 + \eta_{2,K}^2) + \sum_{E\in\Gamma_h} \eta_E^2 \Big)^{1/2} = C\eta. \tag{3.39}$$

□

We end the paper by the following

Remark 3.3 On the the estimate in the $\boldsymbol{H}(\mathrm{div}:\Omega)$-norm. *In the paper we have repeatedly used the fact that by the equilibrium property (2.14) we have* $\mathrm{div}\,(\boldsymbol{\sigma}-\boldsymbol{\sigma}_h) = P_h f - f$ *and hence* $\|\mathrm{div}\,(\boldsymbol{\sigma}-\boldsymbol{\sigma}_h)\|_0 = \|f - P_h f\|_0$ *is a quantity that is directly computable from the data to the problem. For the BDM spaces it furthermore holds that* $\|f-P_h f\|_0 = \mathcal{O}(h^k)$*, whereas* $\|\boldsymbol{\sigma}-\boldsymbol{\sigma}_h\|_0 = \mathcal{O}(h^{k+1})$*, and hence this trivial component in the* $\boldsymbol{H}(\mathrm{div}:\Omega)$ *norm dominates the whole estimate.* □

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