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CONNECTING ATOMISTIC-TO-CONTINUUM COUPLING AND DOMAIN DECOMPOSITION*

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Abstract. Many atomistic/continuum coupling algorithms utilize an overlapping subdomain method, where boundary data for local solves in atomistic and discretized continuum subdomains is provided from local solves in neighboring subdomains. Such coupling algorithms are closely related to the classical alternating Schwarz domain decomposition method, although little to no convergence or error analysis exists for such methods in an atomistic/continuum framework. We consider a specific alternating Schwarz algorithm for coupling a nonlocal atomistic model with a local finite element model and carry out a convergence and error analysis along with supporting numerical experiments.

Key words. atomistic-to-continuum, alternating Schwarz, lattice statics

AMS subject classifications. 65N30, 65F10, 74G45, 82D25

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1. Introduction. Atomistic/continuum coupling[1] methods are motivated by the desire to study material domains on scales where atomistic effects are important but fully atomistic simulation is not feasible. Such coupling schemes call for decomposition of the material domain into atomistic and continuum subdomains, where the continuum subdomain is modeled via a finite element analysis. The treatment of the interface between these subdomains, or "handshake region," is primarily what distinguishes one atomistic/continuum coupling method from another. In this transition region, approximations are made such as treating finite element nodes as atoms, or vice versa, to accommodate the incompatibility between a nonlocal atomistic description and a local finite element description.

A complete theory of this transition region does not yet exist. However, the atomistic/continuum coupling problem has similarities with the classical continuum-to-continuum domain decomposition problem. We will explore some of these similarities and address the extent to which both problems can be placed within the same mathematical and algorithmic framework. We focus only on analysis of methods to couple length scales (statics). Analysis of the many schemes proposed to couple length and time scales (dynamics) is a separate but related problem requiring additional analysis.

Many different approaches to couple atomistic and continuum domains have been proposed; see any of the reviews [30, 9, 26, 38, 13]. Broadly speaking, these approaches can be divided into two categories. The methods in the first category rely

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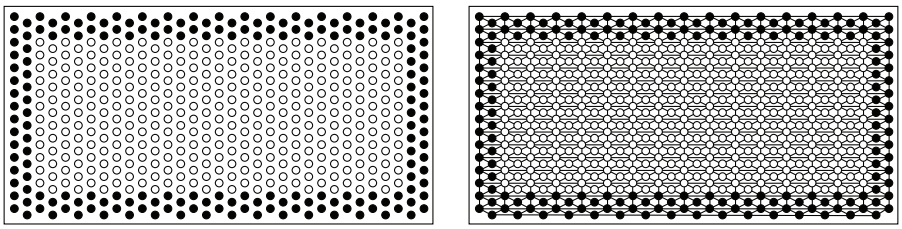
[1]We note here that the name *atomistic/continuum coupling* is a misnomer. We never couple an atomistic model with a continuum model, but only with a discretized continuum model, such as a finite element model.

on a single global energy functional that approximates the total energy of the atomistic/continuum system. The quasi-continuum (QC) method [36, 27], is a well-known technique for coupling atomistic and discretized continuum domains in the static (zero temperature) case, which belongs to this type of method. To deal with the local/nonlocal interface in the transition region, the QC method approximates the global atomic energy functional in the continuum region and the transition region. This has the attractive feature that a single global energy functional is generated with far fewer degrees of freedom than the corresponding global atomistic model. In addition, availability of a single energy functional facilitates analysis of the method. Thus, it is not surprising that, compared to other atomistic/continuum methods, some analysis has been accomplished [18, 24, 5, 25, 11] for the QC method. Unfortunately, to the extent that the energy functional in these methods is an inexact approximation of the true energy in the system, so-called ghost forces are generated and must be explicitly corrected [33]. In general, any coupling approach that generates a well-defined global energy functional must sacrifice accuracy [9].

The second category of atomistic/continuum coupling algorithms avoids this issue altogether by taking an alternative approach to the coupling problem. Utilizing overlapping subdomains, methods in this category perform a solve on the atomistic subdomain, thus generating boundary conditions for the continuum domain, then perform a solve on the continuum domain, thus generating boundary conditions for the atomistic domain, and repeat until convergence. Subdomain solves require only local energy functionals for the atomistic and continuum domains, and thus a global energy functional is never needed. This type of "back-and-forth" iteration process is employed by methods for many different atomistic/continuum coupling problems, including the FEAt method [19], as well as the coupling schemes proposed by Li, Liao, and Yip [21, 22, 23], Hadjiconstantinou [15, 16], Wijesinghe and Hadjiconstantinou [40], Werder, Walther, and Koumoutsakos [39], Tang and Aluru [37], Nie et al. [28], and Nie, Chen, and Robbins [29]. However, the lack of a single, albeit approximate, energy functional makes error analysis of these coupling methods more difficult, despite the fact that this process of back-and-forth iteration between domains is well known[2] within the domain decomposition community as the *alternating Schwarz* [32] method. Although others such as Hadjiconstantinou [15, 16] and Wijesinghe and Hadjiconstantinou [40] have recognized that specific atomistic/continuum coupling schemes are essentially alternating Schwarz, no error or convergence analysis exists. One reason is that the classical alternating Schwarz algorithm is formulated for problems described by a single physical model, valid over both subdomains. As a result, analysis of this algorithm cannot be straightforwardly extended to variants where subdomain problems are defined by different physical models.

The main goal of this paper is to provide analysis of the second class of atomistic/continuum methods, i.e., algorithms characterized by a back-and-forth iteration process and lack of a globally defined energy functional. We have organized the paper as follows. In section 2 we introduce a prototypical atomistic/continuum model and define a specific atomistic/continuum alternating Schwarz coupling algorithm. In section 3 we perform error and convergence analyses on this algorithm. We demonstrate conditions under which the atomistic solution will be recovered. We conduct numerical experiments supporting our analysis in section 4 and offer conclusions in section 5.

[2]For more on this method, see [34, 31].



(a) Example atomic lattice.

(b) Example finite element mesh with triangular elements.

FIG. 2.1. *Example two-dimensional atomic lattice and associated finite element mesh derived from lattice nodes. Dark atoms/nodes are taken to be fixed-displacement (Dirichlet) boundary atoms/nodes.*

2. A prototypical atomistic/continuum model. We begin by defining a global atomistic domain of finite extent, which will consist of a one-, two-, or three-dimensional Bravais-like lattice of atoms. A sample two-dimensional lattice is shown in Figure 2.1(a). We suppose that all atoms share a bond with their rth nearest neighbors ($r \geq 1$), where each bond is represented by a linear spring, to define a mass-spring network. That is, $r = 1$ implies all particles are connected to their nearest neighbors, $r = 2$ implies all particles are connected to their nearest and second-nearest neighbors, etc. We define a corresponding one-, two-, or three-dimensional global finite element domain where the finite element nodes are located at the lattice sites. A sample two-dimensional finite element domain is shown in Figure 2.1(b). For our finite element model, we assume piecewise linear finite element shape functions.

We consider a global finite element model with nodes located at lattice sites only for ease of presentation, as such a model does not reduce the total number of degrees of freedom and thus presents no computational savings over the corresponding global atomistic model. In general, an atomistic domain is coupled with a finite element mesh more coarse than the atomic lattice. In such a coupling, atomistic positions are computed by evaluating the displacement fields of the finite element solution at the undeformed atom position. Likewise, finite element nodal displacements are computed by evaluating the local atomic displacement field in the region around the undeformed nodal position. For ease of presentation, we omit these grid-transfer operators from our analysis.

For simplicity, we assume that we are modeling a homogeneous linear elastic material with some tensile elastic modulus E. Clearly, our global atomistic and finite element models are simply two different descriptions of the same physical material, and we desire that they both permit certain solutions, such as recovering a constant strain under an applied constant stress. In general, we desire that all Cauchy–Born deformations [7, 12] be recovered exactly by the coupled model. The theory to be presented is general in that it does not require that we couple only homogeneous materials and holds for any mass-spring network coupled with any corresponding finite element model.

We briefly describe a desirable (although not necessary) mathematical compatibility relationship between any atomistic and discretized continuum models we might wish to couple and show their connections in Figure 2.2. For several atomistic models, upscaling via an appropriate limit process has been shown to recover an associated continuum PDE. Berezhnyy and Berlyand showed sufficient conditions on a

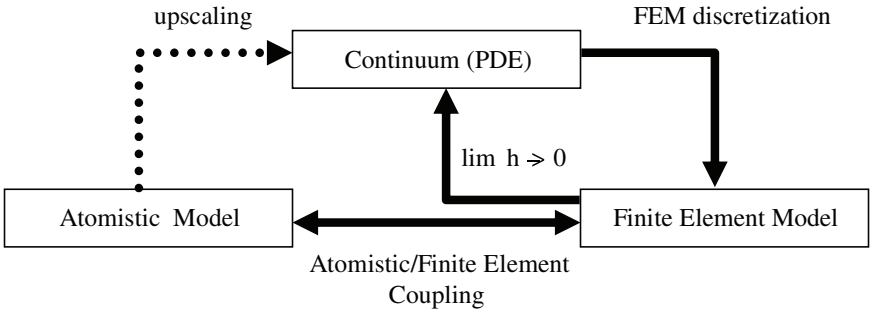


FIG. 2.2. *Desirable mathematical compatibility relationships between three related models. If possible, upscale the atomistic model to a continuum PDE and discretize that PDE to produce the associated finite element model. In this process, one can quantify the relationships between the two models. When the finite element model is local, the local-nonlocal coupling issue arises.*

mass-spring network such that it admits a continuum limit [3]. Blanc, Le Bris, and Lions [6] showed how to write certain continuum mechanical models as an asymptotic limit of molecular models. In [10], E and Huang upscale a Frenkel–Kontorova model to recover the Klein–Gordon equation. Further, Arndt and Griebel show how to recover continuum mechanical models from atomistic models for crystalline solids [1]. Likewise, if our atomistic model is a regular mass-spring network, we may view it as a finite difference discretization of our PDE. However, the atomistic model is not generally directly recoverable from the PDE.

Referring again to Figure 2.2, we see that a finite element discretization of the continuum PDE produces our finite element model, and the PDE can be recovered from that model in the limit where the mesh spacing h goes to zero [8]. Note that our finite element model can then be derived from our atomistic model by first upscaling the atomistic model (presuming that such an upscaling exists) and then applying the method of finite elements to the resulting PDE. We argue that it is desirable to couple atomistic and finite element models that possess this mathematical relationship, because it is possible to precisely quantify the relationships between the two models. In general, one can couple atomistic and finite element models that do not satisfy this relationship, although it then becomes questionable whether the atomistic and finite element models are compatible descriptions of the same material.

In general, we may use any acceptable discretization of our continuum equations. It is important to note that we in general go from a *nonlocal* atomistic model to a *local* finite element model in this process. Interatomic potentials for an atomistic model describing real materials effectively span over many atoms and are thus nonlocal. Common finite element shape functions have local support, meaning that the functions associated with a given node are nonzero only in elements associated with that node, and thus the displacement of any point within an element depends only on the displacements of the nodes of that element. For a more detailed discussion of the differences between local and nonlocal models, see [9]. This local-nonlocal coupling will become the primary focus of our later analysis.

We now describe the specific coupled atomistic/finite element model that we will analyze. Denote the global atomistic domain by Ω_g^a and the global finite element domain by Ω_g^{fe}, such as those depicted in Figure 2.3. For simplicity, we consider the

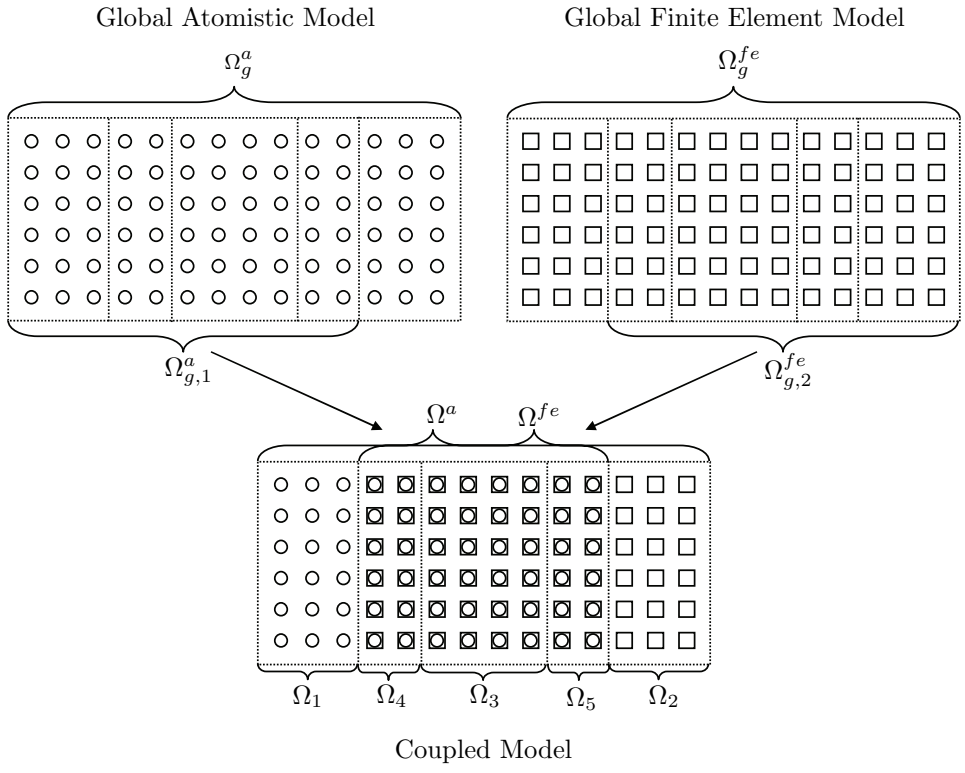


FIG. 2.3. *Construction of a coupled model by overlapping subdomains of atomistic and finite element models. In the coupled model, Ω_1 is the purely atomistic region, Ω_2 the purely finite element region, and $\Omega_3 \cup \Omega_4 \cup \Omega_5$ the overlap region. Circles represent atoms and squares finite element nodes. Both are present in the overlap region of the coupled model.*

case where $\Omega_g^a = \Omega_g^{fe} = \Omega_g$. Assume that Ω_g is subdivided into two overlapping domains $\Omega_g = \Omega_{g,1} \cup \Omega_{g,2}$. We can define corresponding overlapping subdomains on each global model as follows: $\Omega_{g,i}^a = \Omega_g^a \cap \Omega_{g,i}$ and $\Omega_{g,i}^{fe} = \Omega_g^{fe} \cap \Omega_{g,i}$ for $i = 1, 2$.

Now construct a coupled atomistic/finite element model using $\Omega_{g,1}^a$ from the global atomistic model and $\Omega_{g,2}^{fe}$ from the global finite element model, as depicted in Figure 2.3 for a simple two-dimensional case. As our primary focus in this paper is on the coupled model, we will simplify our notation by henceforth referring to the atomistic subdomain *in the coupled model* as Ω^a and the finite element subdomain *in the coupled model* as Ω^{fe}. We can use these domain boundaries to define five nonoverlapping subdomains in the coupled model, which we will call $\Omega_1, \ldots, \Omega_5$. By definition, we have that $\Omega^a = \Omega_1 \cup \Omega_4 \cup \Omega_3 \cup \Omega_5$ and $\Omega^{fe} = \Omega_4 \cup \Omega_3 \cup \Omega_5 \cup \Omega_2$. Ω_1 is the purely atomistic region, Ω_2 the purely finite element region, and $\Omega_3 \cup \Omega_4 \cup \Omega_5$ the overlap region. Both the atomistic and finite element models are defined in the overlap region of the coupled model.[3] Without loss of generality, suppose that the degrees of freedom in Ω_1 are numbered first, those in Ω_2 second, and so on. Additionally, suppose that the degree-of-freedom numberings in the global atomistic and global finite element models match that of the coupled model.

[3]Note that the finite element model is *not* merely the atomistic model reduced to only nearest-neighbor interactions.

When performing a solve in the atomistic subdomain Ω^a, the atoms in subdomain Ω_5 will be held fixed. Correspondingly, in the finite element subdomain Ω^{fe}, the finite element nodes in subdomain Ω_4 are subject to a Dirichlet boundary condition. The size of the subdomain Ω_3 can be altered to control the size of the subdomain overlap. Because the finite element model is a local model, the domain Ω_4 need only be a surface (in three dimensions) or a line (in two dimensions), but the domain Ω_5 must be at least equal to the cutoff radius used in the atomic model. This is to "saturate" the bonds of the atoms in domain Ω_3 (and also possibly Ω_4 or Ω_1) and thus prevent these atoms from acting as if they are in the presence of a surface. The subdomain boundaries in the coupled model are artificial and should never produce surface effects.

Having defined a global atomistic model, a global finite element model, and a coupled model, we now describe the specific alternating Schwarz algorithm we will analyze in the next section.

Algorithm 1 Atomistic/continuum Schwarz

1: Initialize displacements of all non-Dirichlet finite element nodes in Ω^{fe}.
2: Initialize positions of all nonfixed atoms in Ω^a.
3: **while** not converged **do**
4: Fix positions of atoms in domain Ω_5 according to positions of finite element nodes in Ω_5.
5: Solve for displacements of unconstrained atoms in atomistic subdomain Ω^a.
6: Fix displacements of finite element nodes in Ω_4 according to positions of atoms in Ω_4.
7: Solve for displacements of unconstrained finite element nodes in Ω^{fe}.
8: **end while**

Because we do not define a global energy functional, we cannot compute a global residual for our coupled model. Further, if we do define and minimize a global energy functional, our model will be subject to ghost forces, as discussed earlier. Instead, we say that our atomistic/continuum Schwarz algorithm has converged if the relative change in the global solution vector is less than some tolerance ε. The well-known limitation in this convergence test is that it may report convergence prematurely if the algorithm is converging slowly. As we will see later, we have some control over the convergence rate of the algorithm and can avoid this problem in practice. In particular, we will see that the rate of convergence increases with the size of the subdomain overlap.

3. Error and convergence analysis. From the global atomistic and finite element models described above, let us write down the corresponding stiffness matrices and force vectors. For the global atomistic model (corresponding to Figure 2.1(a), for example), we have

$$K_g^a u_g^a = f_g^a, \tag{3.1}$$

and for the global finite element model (corresponding to Figure 2.1(b), for example) we have

$$K_g^{fe} u_g^{fe} = f_g^{fe}, \tag{3.2}$$

where $K_g^a, K_g^{fe} \in \mathbb{R}^{n\times n}$, and $u_g^a, u_g^c, f_g^a, f_g^{fe} \in \mathbb{R}^n$, where n is the number of unconstrained degrees of freedom in the respective global models. Additionally, let there be

n_i unconstrained degrees of freedom in domain Ω_i, $i = 1, \ldots, 5$, with respect to the global models, such that $n = n_1 + n_2 + n_3 + n_4 + n_5$.

Here, u_g^{fe} is the solution of the global finite element model, and u_g^a is the solution of the global atomistic model. In the atomistic model, we clearly can only apply forces to atoms. In our continuum (PDE) model, we can apply body and surface forces, but after a finite element discretization, these forces are realized as nodal forces.

We note here that in Algorithm 1 and for the associated coupled model depicted in Figure 2.3, the finite element problem is not defined over the purely atomistic domain Ω_1. This choice is predicated under the assumption that Ω_1 has features of the solution not resolvable by a continuum model. However, for the purposes of our analysis in this section, we will refer to the global finite element model (3.2), which is defined over all of Ω, including Ω_1. This is done only for the purposes of error and convergence analysis, and (as we will see later) the finite element solution over Ω_1 does not appear in our final error or convergence results.

For clarity, we explain the details of the alternating Schwarz domain decomposition method here. As is well known, the classical alternating Schwarz algorithm can be recast as a projection method [31]. To assist our analysis, we begin by recasting Algorithm 1 as a projection method. Let us define the operators R_1 and R_2 such that the stiffness matrix associated with subdomain Ω^a in our coupled model (see Figure 2.3) can be written as

$$K^a = R_1^T K_g^a R_1,$$

and the stiffness matrix for the finite element subdomain Ω_{fe} in our coupled problem (see Figure 2.3) can be written as

$$K^{fe} = R_2^T K_g^{fe} R_2.$$

Here $R_1 \in \mathbb{R}^{n \times (n_1+n_4+n_3)}$ and $R_2 \in \mathbb{R}^{n \times (n_3+n_5+n_2)}$ are extension operators, and R_1^T and R_2^T are the corresponding restriction operators. Given the atom/node numberings we have defined, they can be written as

$$R_1 = \begin{bmatrix} I & 0 & 0 \\ 0 & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \\ 0 & 0 & 0 \end{bmatrix}, \qquad R_2 = \begin{bmatrix} 0 & 0 & 0 \\ I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & 0 \\ 0 & 0 & I \end{bmatrix},$$

where I represents an identity matrix of appropriate dimension and 0 a zero matrix of appropriate dimension. We may then rewrite the core of Algorithm 1 as the following two steps:

$$\begin{aligned} u_{k+1/2} &= u_k + R_1 (K^a)^{-1} R_1^T (f_g^a - K_g^a u_k), \\ u_{k+1} &= u_{k+1/2} + R_2 (K^{fe})^{-1} R_2^T (f_g^{fe} - K_g^{fe} u_{k+1/2}), \end{aligned}$$

where u_k is the solution to the coupled problem at iteration k, and u_0 is initialized in steps 1 and 2 of Algorithm 1. Substituting in (3.1) and (3.2) gives

$$\begin{aligned} u_{k+1/2} &= u_k + R_1 (K^a)^{-1} R_1^T K_g^a (u_g^a - u_k) &&= u_k + P^a \left(u_g^a - u_k \right), \\ u_{k+1} &= u_{k+1/2} + R_2 (K^{fe})^{-1} R_2^T K_g^{fe} (u_g^{fe} - u_{k+1/2}) &&= u_{k+1/2} + P^{fe} \left(u_g^{fe} - u_{k+1/2} \right), \end{aligned}$$

where $P^a \equiv R_1(K^a)^{-1}R_1^T K_g^a$ and $P^{fe} \equiv R_2(K^{fe})^{-1}R_2^T K_g^{fe}$ are projection matrices. In particular, P^a is a K_g^a-orthogonal projector onto the space $\mathcal{R}(R_1)$, and P^{fe} is a K_g^{fe}-orthogonal projector onto the space $\mathcal{R}(R_2)$, where $\mathcal{R}$ denotes the range of a matrix.

We are interested in conditions for which our coupled model recovers the global atomistic solution u_g^a. To that end, we define the error at step k with respect to the global atomistic solution as $e_k^a \equiv u_k - u_g^a$. Further, we define the vector d such that $u_g^{fe} = u_g^a + d$. That is, d may be viewed as the difference of the global finite element and global atomistic solutions.

Combining the two-step algorithm above into a single step and substituting in our definition for d gives

$$u_{k+1} = \left[I - (P^a + P^{fe} - P^{fe}P^a)\right] u_k + (P^a + P^{fe} - P^{fe}P^a)u_g^a + P^{fe}d.$$

Now subtract u_g^a from both sides to give

$$e_{k+1}^a = \left[I - (P^a + P^{fe} - P^{fe}P^a)\right] e_k^a + P^{fe}d. \tag{3.3}$$

The rightmost term arises due to the "discrepancies" between the atomistic and the continuum models. In some simple cases, e.g., assuming nearest-neighbor interactions only and a linear spring model, this term vanishes. However, it is clear that, for most atomistic models of interest, this term will not disappear.

Let us suppose that the iteration operator has the eigendecomposition $V\Lambda V^{-1}$. Upon substitution, we have

$$e_{k+1}^a = V\Lambda^{k+1}V^{-1}e_0^a + \sum_{i=0}^{k} V\Lambda^i V^{-1}\left(P^{fe}d\right).$$

Let σ be the spectral radius of Λ, and let $\kappa(V) \equiv \|V\|\left\|V^{-1}\right\|$ denote the condition number of the eigenvector matrix V, where $\|\cdot\|$ denotes the 2-norm. Taking norms, we have

$$\begin{aligned}\left\|e_{k+1}^a\right\| &\le \kappa(V)\left\|e_0^a\right\|\sigma^{k+1} + \kappa(V)\left\|P^{fe}d\right\|\sum_{i=0}^{k}\sigma^i \\ &= \kappa(V)\left\|e_0^a\right\|\sigma^{k+1} + \kappa(V)\left\|P^{fe}d\right\|\frac{1-\sigma^{k+1}}{1-\sigma}.\end{aligned}$$

With the preceding equation, we have just proved the following theorem.

THEOREM 3.1. *Assume $\sigma \neq 1$. The norm of the error with respect to the global atomistic model at iteration $k+1$ of Algorithm 1 can be bound above as*

$$\left\|e_{k+1}^a\right\| \le \sigma^{k+1}\kappa(V)\left(\left\|e_0^a\right\| - \frac{\left\|P^{fe}d\right\|}{1-\sigma}\right) + \frac{\kappa(V)}{1-\sigma}\left\|P^{fe}d\right\|. \tag{3.4}$$

If $0 < \sigma < 1$, then in the limit as $k \to \infty$, the first term on the right-hand side disappears, and the second is independent of k. Further, σ determines the convergence rate. So, with respect to the global atomistic solution, the (nonconvergent) rightmost term bounds our error. Note that if σ decreases with increasing overlap, we expect faster convergence of our iterative method, and a smaller rightmost term, both of which are incentive to increase the overlap.

We analyze these two terms separately.

3.1. The convergent term. To analyze the convergence rate we must determine σ, which we can do by considering the block structure of the iteration operator. We utilize analysis similar to that of Bjørstad [4]. We begin by writing out the global stiffness matrices for the atomistic and finite element models, where the block structure of the these matrices indicates the subdomain connectivity:

$$K_g^a = \begin{bmatrix} K_{1,1}^a & 0 & 0 & K_{1,4}^a & 0 \\ 0 & K_{2,2}^a & 0 & 0 & K_{2,5}^a \\ 0 & 0 & K_{3,3}^a & K_{3,4}^a & K_{3,5}^a \\ K_{1,4}^{a^T} & 0 & K_{3,4}^{a^T} & K_{4,4}^a & 0 \\ 0 & K_{2,5}^{a^T} & K_{3,5}^{a^T} & 0 & K_{5,5}^a \end{bmatrix},$$

$$K_g^{fe} = \begin{bmatrix} K_{1,1}^{fe} & 0 & 0 & K_{1,4}^{fe} & 0 \\ 0 & K_{2,2}^{fe} & 0 & 0 & K_{2,5}^{fe} \\ 0 & 0 & K_{3,3}^{fe} & K_{3,4}^{fe} & K_{3,5}^{fe} \\ K_{1,4}^{fe^T} & 0 & K_{3,4}^{fe^T} & K_{4,4}^{fe} & 0 \\ 0 & K_{2,5}^{fe^T} & K_{3,5}^{fe^T} & 0 & K_{5,5}^{fe} \end{bmatrix}.$$

Before writing down the projectors we define specific Schur complement operators that will occur frequently:

$$S_4^a = K_{4,4}^a - K_{1,4}^{a^T}(K_{1,1}^a)^{-1}K_{1,4}^a - K_{3,4}^{a^T}(K_{3,3}^a)^{-1}K_{3,4}^a,$$
$$S_5^{fe} = K_{5,5}^{fe} - K_{2,5}^{fe^T}(K_{2,2}^{fe})^{-1}K_{2,5}^{fe} - K_{3,5}^{fe^T}(K_{3,3}^{fe})^{-1}K_{3,5}^{fe}.$$

Applying the definition of the projectors, we see that they take the form

$$P^a \equiv R_2^T(K^{fe})^{-1}R_2K^{fe} = \begin{bmatrix} I & 0 & 0 & 0 & P_{1,5}^a \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & I & 0 & P_{3,5}^a \\ 0 & 0 & 0 & I & P_{4,5}^a \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$P^{fe} \equiv R_1^T(K^a)^{-1}R_1K^a = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & I & 0 & P_{2,4}^{fe} & 0 \\ 0 & 0 & I & P_{3,4}^{fe} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & P_{5,4}^{fe} & I \end{bmatrix},$$

where the block submatrices take the form

$$P_{1,5}^a = (K_{1,1}^a)^{-1}K_{1,4}^a(S_4^a)^{-1}K_{3,4}^{a^T}(K_{3,3}^a)^{-1}K_{3,5}^a,$$
$$P_{3,5}^a = (K_{3,3}^a)^{-1}\left(K_{3,5}^a + K_{3,4}^a(S_4^a)^{-1}K_{3,4}^{a^T}(K_{3,3}^a)^{-1}K_{3,5}^a\right),$$
$$P_{4,5}^a = -(S_4^a)^{-1}K_{3,4}^{a^T}(K_{3,3}^a)^{-1}K_{3,5}^a,$$
$$P_{2,4}^{fe} = (K_{2,2}^{fe})^{-1}K_{2,5}^{fe}(S_5^{fe})^{-1}K_{3,5}^{fe^T}(K_{3,3}^{fe})^{-1}K_{3,4}^{fe},$$
$$P_{3,4}^{fe} = (K_{3,3}^{fe})^{-1}\left(K_{3,4}^{fe} + K_{3,5}^{fe}(S_5^{fe})^{-1}K_{3,5}^{fe^T}(K_{3,3}^{fe})^{-1}K_{3,4}^{fe}\right),$$
$$P_{5,4}^{fe} = -(S_5^{fe})^{-1}K_{3,5}^{fe^T}(K_{3,3}^{fe})^{-1}K_{3,4}^{fe}.$$

We now have that

$$P^a + P^{fe} - P^{fe}P^a = \begin{bmatrix} I & 0 & 0 & 0 & P^a_{1,5} \\ 0 & I & 0 & 0 & -P^{fe}_{2,4}P^a_{4,5} \\ 0 & 0 & I & 0 & -P^{fe}_{3,4}P^a_{4,5} \\ 0 & 0 & 0 & I & P^a_{4,5} \\ 0 & 0 & 0 & 0 & I - P^{fe}_{5,4}P^a_{4,5} \end{bmatrix}.$$

Clearly, the iteration operator $I - (P^a + P^{fe} - P^{fe}P^a)$ is a block upper-triangular matrix with zero blocks on all but the last entry of the diagonal, which is equal to $P^{fe}_{5,4}P^a_{4,5}$. Thus, we have that σ is the maximum magnitude eigenvalue of $P^{fe}_{5,4}P^a_{4,5}$.

In general, $0 < \sigma$ so long as the atomistic lattice is stable and a stable finite element formulation is used. From practical experience, one may expect that if the finite element formulation in $\Omega \setminus \Omega_1$ can be derived from the atomistic model in the manner suggested by Figure 2.2, then $\sigma < 1$. We give more detail in Appendix A on situations where $\sigma < 1$.

3.2. The nonconvergent term. To analyze the behavior of the rightmost term in our bound, we must consider $\|P^{fe}d\|$. As we have broken our global domain into five subdomains $\Omega_1, \ldots, \Omega_5$, we also break the vector d into five subvectors such that $d = \left[d_1^T, d_2^T, d_3^T, d_4^T, d_5^T\right]^T$.

In general, the domain Ω_1 was chosen to be purely atomistic in the coupled model because a finite element solution in this domain does not produce acceptable results. Thus, we expect the finite element solution and the atomistic solution in the domain Ω_1 to be different. That is, we expect that $d_1 \neq 0$. Fortunately, this does not prohibit our coupled model from recovering the global atomistic solution. For this, a key role is played by the structure P^{fe}. This operator acts only on the portions of the global problem that are in the finite element domain Ω^{fe} and ignores the purely atomistic subdomain Ω_1. As a result,

$$\begin{aligned} \left\|P^{fe}d\right\|_2^2 = \left\|d_2 + P^{fe}_{2,4}d_4\right\|^2 + \left\|d_3 + P^{fe}_{3,4}d_4\right\|^2 + \left\|P^{fe}_{5,4}d_4 + d_5\right\|^2 \\ \sim \|d_2\|^2 + \|d_3\|^2 + \|d_4\|^2 + \|d_5\|^2; \end{aligned}$$

i.e., the value of d_1 (the difference of the atomistic and continuum solutions *in the purely atomistic subdomain* Ω_1) does not appear in the nonconvergent term.

We will see in the next section that the error of the converged solution depends not only on the location but also the size of the pad region.

We can easily identify one situation when we expect $\|P^{fe}d\| = 0$. In particular, we will have $d_i = 0$, $i = 2, \ldots, 5$, if the atomistic and finite element displacements are identical in domains $\Omega_2, \ldots \Omega_5$. This means that the displacement of the macroscopic model (the finite element model) matches exactly the displacement of the microscopic model (the atomistic model) in the domain Ω^{fe}.

REMARK 3.2. *We expect that $\|P^{fe}d\| = 0$ if the deformation in Ω^{fe} is a Cauchy–Born deformation, regardless of the deformation in Ω_1.*

In particular, our linear spring model and our choice of finite element shape functions can both reproduce exactly a constant strain solution under an applied constant stress. In finite element parlance, recovering a constant strain solution given an applied constant stress satisfies a *patch test* [35]. We consider this specific example in section 4.2.

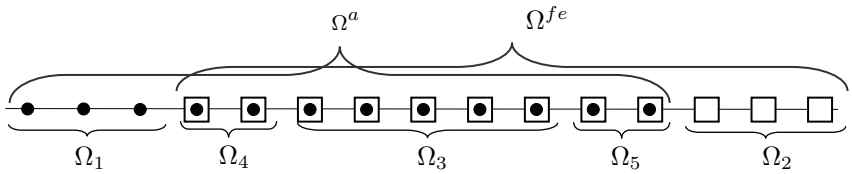


FIG. 4.1. *The overlap region for the one-dimensional coupled model consists of domains Ω_4, Ω_3, and Ω_5. In this figure, circles represent atoms and squares finite element nodes. When solving in domain Ω^a, the atoms in domain Ω_5 are held fixed. When solving in domain Ω^{fe}, the finite element nodes in domain Ω_4 are held fixed.*

4. Numerical results. The results in the previous section are general in that they do not depend on the number of dimensions of the model, the shape of the atomistic or finite element subdomains, the finite element discretization, or the specifics of the mass-spring model used in the atomistic subdomain. To demonstrate theoretical results, we will propose a specific one-dimensional model and then analyze it.

4.1. A one-dimensional overlapping Schwarz model. Here we propose one-dimensional atomistic, finite element, and coupled models based on the one-dimensional models described in [9]. In particular, Algorithm 1 applied to the model we describe below is essentially identical to the one-dimensional FEAt example from [9]. Our global atomistic model is represented by a mass-spring system of 105 atoms with lattice constant α, where nearest-neighbor atoms are bonded by a spring of stiffness k_1^a and second-neighbor atoms are bonded by a spring of stiffness k_2^a. (Hence, we have a second-nearest neighbor model with $r = 2$.) We number the atoms/nodes from left to right, $1, \ldots, 105$. The two leftmost and two rightmost atoms will be held fixed in all cases. Our global finite element model will consist of 104 truss elements, where the two rightmost and two leftmost nodes are held fixed; i.e., there we impose Dirichlet boundary conditions. In particular, the fixed atom positions of the atomistic model and fixed displacements of the Dirichlet finite element nodes will be set consistently. Each finite element has an equilibrium length α and Young's modulus such that the effective spring constant is k^{fe}. Under a uniform deformation field, we would like the strain energies of the two models to match, so we fix $k^{fe} = 4k_1^a + k_2^a$. We construct a coupled model by overlapping an atomistic subdomain with a finite element subdomain, as discussed in section 2. Domain Ω_1 denotes a purely atomistic subdomain, domain Ω_2 a purely finite element subdomain, and domains Ω_3, Ω_4, and Ω_5 the subdomains in the overlap region. When solving for new atom positions in the atomistic subdomain Ω^a, we hold the atoms in domain Ω_5 fixed. Since $r = 2$ for our model, we have only two atoms in domain Ω_4. In general, the number of fixed-displacement atoms must be large enough to avoid the appearance of surface effects in the overlap region. The subdomain boundaries here are artificial, and surface effects are nonphysical. Likewise, when solving for new node positions in the finite element subdomain Ω^{fe}, we hold the nodes in domain Ω_4 fixed. As our finite element shape functions have only local support, we require only one Dirichlet node in subdomain Ω_4. However, to avoid coupling between domains Ω_1 and Ω_3 in the atomistic model, instead we define Ω_4 to include two atoms/nodes. The region around the interface is depicted in Figure 4.1.

To study how overlap affects convergence, we define an overlap parameter δ, as shown in Figure 4.2. Let the middle atom/node in the coupled model be denoted as I. An overlap of $\delta = 1$ specifies one overlapping atom/node to the left and right of atom/node I, an overlap of $\delta = 2$ specifies two overlapping atoms/nodes to the left and right of atom/node I, etc. Recall that we are considering an atomistic model

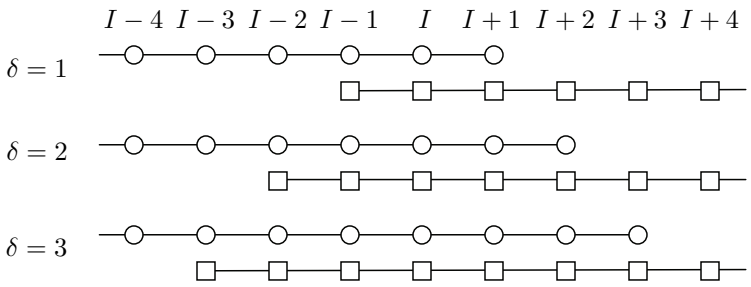


FIG. 4.2. *The overlap region for the one-dimensional coupled model for various values of overlap δ. Let circles denote atoms and squares denote finite element nodes, with the middle atom/node as I.*

TABLE 4.1
Data for section 4.2*: constant strain.*

δ	Convergence rate	σ	Num. iterations	$\|u - u_g^a\|$	2nd term from (3.4)	$\|P^{fe}d\|$
2	.9195	.9195	287	1.09×10^{-12}	3.11×10^{1}	4.16×10^{-17}
3	.8501	.8501	153	5.37×10^{-13}	1.79×10^{-2}	4.48×10^{-17}
4	.7859	.7859	106	2.90×10^{-13}	7.82×10^{-4}	4.82×10^{-17}
5	.7264	.7264	93	2.20×10^{-13}	1.69×10^{-5}	4.57×10^{-17}

with $r = 2$ (nearest-neighbor and second-nearest-neighbor coupling). As a result, we will consider only configurations where domain Ω_3 has at least two atoms in order to avoid direct coupling between domains Ω_4 and Ω_5. This means we will consider only overlap values of $\delta \geq 2$.

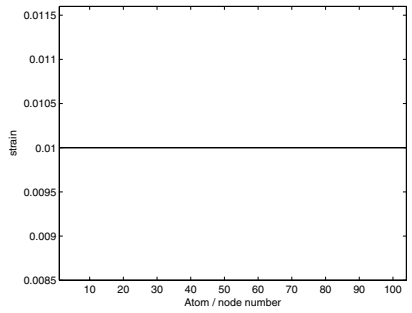
Referring to Figure 2.2, we note that the particular one-dimensional mass-spring model we use can easily be shown to be a finite difference discretization with a particular stencil of the equation

$$-\frac{d}{dx}\left(k^{fe}\frac{du}{dx}\right) = f.$$

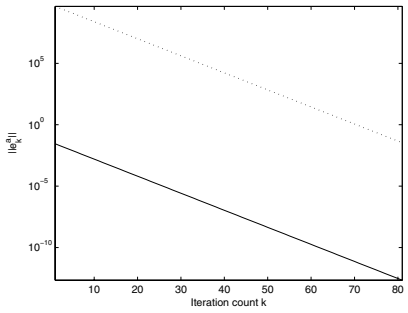
In the limit as the lattice constant goes to zero, this PDE is recovered. Further, our finite element model is a finite element discretization of the same PDE and likewise recovers this PDE in the limit as the mesh spacing goes to zero.

4.2. Constant strain. We first examine the ability of the coupled model to reproduce a constant-strain solution. We begin by setting two leftmost atoms and the two rightmost finite element nodes to have a position/displacement consistent with a constant strain of 0.01. We also fix the position of the leftmost atom at the origin. We solved the coupled model using Algorithm 1 with a convergence tolerance of $\varepsilon = 1.0 \times 10^{-13}$ for several values of δ. Convergence data is shown in Table 4.1. A plot of the computed strain solution for the coupled model is shown in Figure 4.3(a), showing a constant strain throughout the domain, including the overlap region. For these boundary conditions, $\|d\| = 9.2 \times 10^{-17}$. In particular, this means $\|d_2\| = \|d_3\| = \|d_4\| = \|d_5\| = 0$ to within machine precision (see the last column of Table 4.1), which is precisely the case where the coupled model can recover the global atomistic solution. The bound (3.4) is plotted in Figure 4.3(b).

One item of note is that $\kappa(V)$ (the condition number of the eigenvector matrix) is quite large. The iteration operator is nonsymmetric, so this is not unexpected.



(a) Computed strain for global atomistic model and coupled model. (Curves are identical.)



(b) Convergence curve (solid line) and bound (3.4) (dashed line) for $\delta = 5$.

FIG. 4.3. *Plots for section* 4.2*: constant strain.*

TABLE 4.2
Data for section 4.3*: point force in pure atomistic domain* Ω_1.

δ	Convergence rate	σ	Num. iterations	$\|u - u_g^a\|$	2nd term from (3.4)	$\|P^{fe}d\|$
2	.9195	.9195	288	1.12×10^{-12}	4.24×10^{1}	5.65×10^{-17}
3	.8501	.8501	154	5.06×10^{-13}	2.49×10^{-2}	2.49×10^{-17}
4	.7859	.7859	106	3.20×10^{-13}	9.69×10^{-4}	9.69×10^{-17}
5	.7264	.7264	81	2.42×10^{-13}	2.11×10^{-5}	2.11×10^{-17}

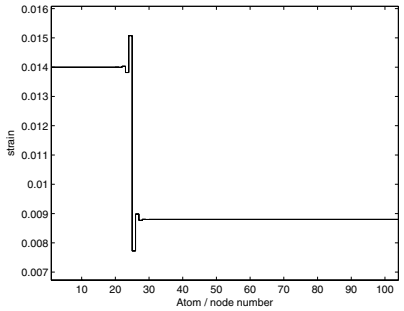
In this example, the bound (3.4) is useful in that it predicts when the error can be zero, even though it is not numerically tight. One alternative approach is to modify Algorithm 1 to a symmetric alternating Schwarz algorithm. In this algorithm, the iteration operator becomes symmetric, thus forcing its eigenvector matrix to have a condition number of one. Although producing a tighter bound, this symmetric version of the algorithm is less useful in practice, as it is more expensive per iteration.

4.3. A point force in the atomistic subdomain. In this section, we consider applying a point force to atom 25 in the atomistic subdomain and study how well the global atomistic solution is recovered by the coupled model.

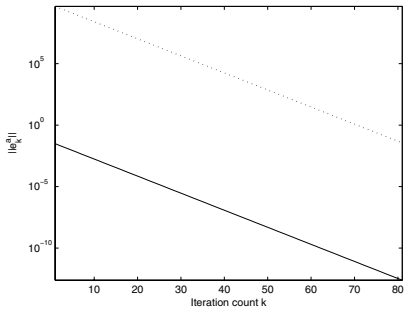
To set the positions of the fixed atoms and nodes in the finite element model, we proceed by attempting to match the local strains at the ends with those of a global finite element model. We first solve the global finite element problem setting the four Dirichlet nodes such that a constant strain of 0.01 results in the absence of external forces. We then fix the two leftmost atom and two rightmost finite element node positions to match those of the global finite element model. Without loss of generality, the leftmost atom is always held fixed at the origin.

We solved the coupled model using Algorithm 1 with a convergence tolerance of $\varepsilon = 1.0 \times 10^{-13}$ for several values of δ. Convergence data is shown in Table 4.2. A plot of the computed strain for the coupled model is shown in Figure 4.4(a), showing a jump in the strain at the point of application of the force. The bound (3.4) is plotted in Figure 4.4(b).

For this case, $\|d\| \approx 9.1 \times 10^{-6}$. Although $\|d_1\| \neq 0$, we have $\|d_2\| = \|d_3\| = \|d_4\| = \|d_5\| = 0$ to within machine precision (see the last column of Table 4.2), allowing the coupled model to again recover the global atomistic solution. That



(a) Computed strain for global atomistic model and coupled model. (Curves are identical.)



(b) Convergence curve (solid line) and bound (3.4) (dashed line) for $\delta = 5$.

FIG. 4.4. *Plots for section* 4.3*: point force in pure atomistic domain* Ω_1.

TABLE 4.3
Data for section 4.4*: point force in overlap domain* Ω_3.

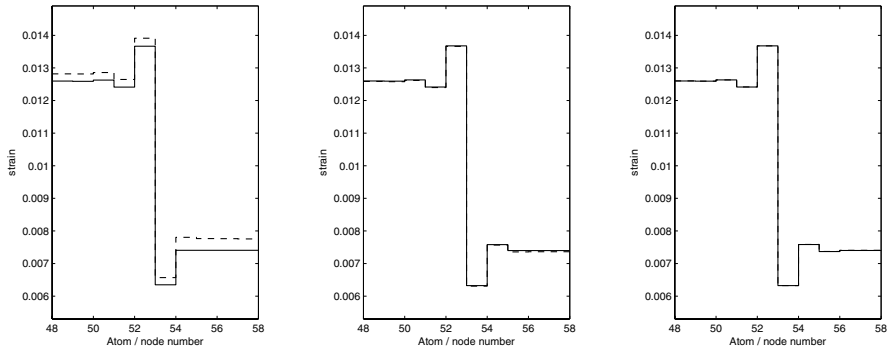
δ	Convergence rate	σ	Num. iterations	$\|u - u_g^a\|$	2nd term from (3.4)	$\|P^{fe}d\|$
2	.9195	.9195	290	1.77×10^{-5}	8.92×10^{12}	1.19×10^{-5}
3	.8501	.8501	154	1.66×10^{-6}	3.59×10^{9}	9.00×10^{-6}
4	.7859	.7859	106	2.02×10^{-7}	1.48×10^{8}	9.13×10^{-6}
5	.7264	.7264	82	2.78×10^{-8}	3.36×10^{6}	9.10×10^{-6}

is, the atomistic and finite element models disagree only in Ω_1, a domain we have designated to be a purely atomistic domain, and so our coupled model will recover the global atomistic solution.

4.4. A point force in the overlap region. In this section, we apply a point force to atom I in the coupled model, essentially the worst location to apply a force, and study how well the global atomistic solution is recovered by the coupled model.

We set the fixed-displacement atoms and nodes as in the previous section. We then solved the coupled model using Algorithm 1 with a convergence tolerance of $\varepsilon = 1.0 \times 10^{-13}$ for several values of δ. Convergence data is shown in Table 4.3. A plot of the computed strain near the pad region is in Figure 4.5 for several values of δ. Observe that the quality of the solution improves as δ increases, meaning that the error depends not only on the placement of the overlap region (with respect to the location of the point force) but also varies with the size of the overlap. This result is in sharp contrast to convergence results for alternating Schwarz applied to a standard finite element discretization of an elliptic PDE; see, for example, [34, 31]. In this example we have a nonuniform displacement field in the overlap region. Correspondingly, we notice that $\|P^{fe}d\|$ in Table 4.3 does not decrease below a minimum value and is much larger than $\|P^{fe}d\|$ in Tables 4.1 and 4.2. The nonconvergent term in (3.4) is not small in this example, and so the error in the converged solution is larger as well.

4.5. Coupling Lennard-Jones and finite element models. In this section, we couple a one-dimensional Lennard-Jones atomistic model [20] with our finite element model and study how well the global atomistic solution is recovered by the coupled model. The well-known Lennard-Jones potential can be written as



(a) $\delta = 2$ (b) $\delta = 3$ (c) $\delta = 4$

FIG. 4.5. *Plots for section* 4.4*: point force in overlap domain* Ω_3*. Computed strains are shown for the global atomistic model (dashed line) and the coupled model (solid line). The* $\delta = 5$ *strain plot (not shown) is visually indistinguishable from the* $\delta = 4$ *strain plot.*

TABLE 4.4
Data for section 4.5*: Coupling a Lennard-Jones and finite element model with a point force in pure atomistic domain* Ω_1*.*

δ	Convergence rate	Num. iterations	$\|u - u_g^a\|$
2	.9258	241	1.92×10^{-5}
3	.8569	126	1.92×10^{-5}
4	.7930	87	1.92×10^{-5}
5	.7336	67	1.92×10^{-5}

$$U_{ij} = 4\epsilon \left(\left(\frac{s}{r_{ij}} \right)^{12} - \left(\frac{s}{r_{ij}} \right)^{6} \right),$$

where $r_{ij} = |x_i - x_j|$ is the distance between two atoms. For this model, we fixed $\epsilon = 1/4$, $s = 2\sqrt[3]{2}$ and set a lattice constant $\alpha = \sqrt[6]{2}s$. Additionally, we set a cutoff of $2.5s$.

To match the Lennard-Jones with our finite element model, we linearized the Lennard-Jones force and set the stiffness k^{fe} to match the linearized Lennard-Jones force, so that both models will agree to first order, and hence only for small deformations.

We set the fixed-displacement atoms and nodes as in the previous section and apply a point force to atom 25, just as in section 4.3. We then solve the coupled model using Algorithm 1 with a convergence tolerance of $\varepsilon = 1.0 \times 10^{-13}$ for several values of δ. Convergence data is shown in Table 4.4. We observe an increase in convergence rate with increasing δ, just as when we coupled with a mass-spring model. We also observe that the absolute error is essentially constant with δ, which we expect, given that the point force is applied far from the overlap region.

5. Conclusions. In this paper we analyzed an important class of atomistic/ continuum coupling methods that are characterized by a "back-and-forth" iteration process between overlapping atomistic and continuum subdomains. These methods do not rely on a single, global energy functional, and so they avoid ghost forces. Our

analysis takes advantage of the fact that such methods may be placed within the framework of the alternating Schwarz domain decomposition algorithm.

However, in contrast to classical alternating Schwarz applied to a single PDE model, we showed that the error in the atomistic/continuum version of this method consists of *convergent* and *nonconvergent* parts. As a result, unlike the classical case, in the atomistic/continuum setting the error can depend not only on the size but also the placement of the overlap region with respect to external applied forces. Among other things this implies that the atomistic/continuum solution computed in this way depends on the size of the overlap region. In particular, based on our experiments, it is clear the overlap region should be placed sufficiently far away from regions where the continuum model is not valid.

In closing, we observe that many improvements have been made to the classical alternating Schwarz domain decomposition algorithm, including acceleration by modification of the transmission conditions between subdomains [14]. A next logical step is to extend these acceleration techniques to the atomistic/continuum setting.

Appendix A. A class of problems for which $\sigma < 1$. In this section we consider a large class of problems for which we can prove $\sigma < 1$, showing that the first term on the right-hand side of (3.4) (the "convergent term" discussed in section 3.1) disappears in the limit as $k \to \infty$. Sufficient (but not necessary) conditions to satisfy the assumptions of Theorem A.1 on K_g^{fe}, K_g^a from (3.1) and (3.2) are that K_g^a is a mass-spring system,[4] that a sufficiently regular finite element mesh was used in generating K_g^{fe}, and that K_g^a, K_g^{fe} are compatible models.

Before we present Theorem A.1, we present some notation. If the entries of the matrix A are nonnegative (positive), we say that the matrix is nonnegative (positive) and denote this as $A \geq O$ ($A > O$), and similarly for vectors. A matrix A is a nonsingular M-matrix if its off-diagonal elements are nonpositive and it is monotone, i.e., $A^{-1} \geq O$ [17]. Given a positive vector $w > O$, the weighted max-norm for a vector y is defined as

$$\|y\|_w = \max_j \left| \frac{1}{w_j} y_j \right|,$$

and the corresponding matrix norm is defined as

$$\|A\|_w = \max_i \frac{(|A|\, w)_i}{w_i}.$$

For $A \geq O$, $Aw < w$ implies $\|A\|_w < 1$ [2]. In the following, we will denote the Schwarz iteration operator from (3.3) as T, where we write T as

$$T = (I - P^{fe})(I - P^a) = T^{fe} T^a.$$

THEOREM A.1. *Let K_g^{fe} and K_g^a in* (3.1) *and* (3.2) *be M-matrices, with $K_g^{fe}(K_g^a)^{-1} \geq O$. Let σ be the spectral radius of the Schwarz operator from* (3.4). *Then for any vector $w = (K_g^a)^{-1} e$ with $e \geq O$, $\sigma \leq \|T\|_w < 1$.*

The proof below is a modification of [2, Lemma 3.1].

[4]The mass-spring system may be viewed as a linearization of a more complicated potential. Given the choice of potential and positions of the particles, if the nearest-neighbor distance is in the convex region of the potential and nearest-neighbor interactions dominate, the resulting matrix K_g^a will be symmetric positive definite and thus an M-matrix, satisfying the conditions of Theorem A.1. See [24] for further details.

Proof. We wish to show that $\sigma < 1$, where σ is the spectral radius of T. Given that $\sigma \leq \|T\|_w$ [2, Lemma 3.1], we accomplish this by proving $T \geq O$ and $Tw \leq w$, thus demonstrating $\|T\|_w < 1$.

To show $T \geq O$, we observe from [2, Lemma 3.1] that $T^{fe} \geq O$, $T^a \geq O$, and thus $T \geq O$.

Next, we show that $Tw < w$ with $w = (K_g^a)^{-1}e$, where $e > O$. We consider the first step (application of T^a) separately from the second step (application of T^{fe}). In the following, let S_1 denote the indices of the degrees of freedom in $\Omega_{g,1}^a$, and similarly let S_2 denote the indices of the degrees of freedom in $\Omega_{g,2}^{fe}$, following Figure 2.3. $S_1 \cup S_2$ contains all the degrees of freedom for the global model, and $S_1 \cap S_2$ contains the degrees of freedom in $\Omega_3 \cup \Omega_4 \cup \Omega_5$.

Let $w_1 = T^a w$. From [2, Lemma 3.1], we have that $0 \leq w_1 \leq w$, with strict inequality in the components corresponding to S_1. Writing $(w_1)_i$ as the ith component of w_1, we have

$$(w_1)_i \begin{cases} = w_i & \text{if } i \notin S_1, \\ < w_i & \text{if } i \in S_1. \end{cases}$$

Now let $w_2 = T^{fe} w_1$, and observe that

$$\begin{aligned} w_2 = T^{fe} w_1 &= T^{fe}(w_1 - w + w) \\ &= T^{fe}(w_1 - w) + T^{fe} w. \end{aligned}$$

For $i \in S_2$, the ith component of w_2 can be written as

$$(w_2)_i = \left[T^{fe}(w_1 - w)\right]_i + \left[w - R_2 (K_g^{fe})^{-1} R_2^T K_g^{fe} (K_g^a)^{-1} e\right]_i,$$

where we have used the definition of P^{fe} from section 3. Because $T^{fe} \geq O$, $w_1 - w \leq O$, $R_2 (K_g^{fe})^{-1} R_2^T \geq O$ [2, Proposition 2.3], $K_g^{fe}(K_g^a)^{-1} \geq O$, and $e > O$, we have shown that $w_2 \leq w$, and in the components corresponding to S_2 the inequality is strict. We can again have

$$(w_2)_i \begin{cases} = (w_1)_i \leq w_i & \text{if } i \notin S_2, \\ < w_i & \text{if } i \in S_2. \end{cases}$$

Because $S_1 \cup S_2$ contains all degrees of freedom, we conclude that $Tw < w$. It follows that $\|T\|_w < 1$, and therefore $\sigma < 1$. ∎

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