Integral identities for an interfacial crack in an anisotropic bimaterial with an imperfect interface

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Abstract

We study a crack lying along an imperfect interface in an anisotropic bimaterial. A method is devised where known weight functions for the perfect interface problem are used to obtain singular integral equations relating the tractions and displacements for both the in-plane and out-of-plane fields. The integral equations for the out-of-plane problem are solved numerically for orthotropic bimaterials with differing orientations of anisotropy and for different extents of interfacial imperfection. These results are then compared with finite element computations.

Keywords: singular integral equations, anisotropic bimaterial, imperfect interface, crack, weight function

1. Introduction

Singular integral equations have played a significant role in the study of crack propagation in elastic media since their introduction by Muskhelishvili (1963) and have garnered much scientific attention (Sneddon, 1972). They have been used in the analysis of crack problems in complex domains containing an arbitrary number of wedges and layers separated by imperfect interfaces (Mishuris, 1997a,b); the resulting singular integral equations with fixed point singularities have been analysed by Duduchava (1979), based on the theory of linear singular operators (Gohberg and Krein, 1960). More recently, singular integral equations have been applied to problems involving interfacial cracks in both isotropic (Piccolroaz and Mishuris, 2013; Mishuris et al., 2013) and anisotropic bimaterials (Morini et al., 2013a). This paper extends the singular integral equation approach to an anisotropic bimaterial containing an imperfect interface.

Interfacial problems concerning a semi-infinite crack along a perfect interface in an anisotropic bimaterial have been considered in Suo (1990) through the use of the formalisms proposed by Stroh (1962) and Lekhnitskii (1963). Expressions were found for the stress intensity factors at the crack tip under the restriction of symmetric loading on the crack faces. Using weight function techniques introduced by Bueckner (1985) and developed further by Willis and Movchan (1995), an approach was developed to find stress intensity factors for an interfacial crack along a perfect interface under asymmetric loading for both the static and dynamic cases, see Morini et al. (2013b) and Pryce et al. (2013) respectively. More widely, weight functions are well developed in the literature for a wide range of fractured body geometries and allow for the evaluation of important constants that may act as fracture criteria. For instance, weight functions have been obtained for a corner crack in a plate of finite thickness (Zheng et al., 1996), a 3D semi-infinite crack in an infinite body (Kassir and Sih, 1973) and a crack lying perpendicular to the interface in a thin surface layer (Fett et al., 1996).

Imperfect interfaces provide a more physically realistic interpretation of a bimaterial than a perfect one, accounting for the fact that the interface between two materials is rarely sharp. Atkinson (1977) took this into account by suggesting the interface be replaced with a thin strip of finite thickness, which
provided the bonding material occupying the strip is sufficiently soft may be replaced by so-called imperfect interface transmission conditions. These allow for an interfacial displacement jump in direct proportion to the traction, which is itself continuous across the interface (Antipov et al., 2001; Lenci, 2001; Mishuris, 2001). Such transmission conditions alter physical fields near the crack tip significantly; for instance the usual perfect interface square root stress singularity is no longer present and is instead replaced by a logarithmic singularity (Mishuris and Kuhn, 2001), although tractions remain bounded along the interface. More general imperfect interface transmission conditions were derived by Benveniste and Miloh (2001) which considered a thin curved isotropic layer of constant thickness, while Benveniste (2006) presented a general interface model for a 3D arbitrarily curved thin anisotropic interphase between two anisotropic solids. Weight function techniques have been recently been adapted to imperfect interface settings to quantify crack tip asymptotics in thin domains (Vellender et al., 2011), analyse problems of waves in thin waveguides (Vellender and Mishuris, 2012) and conduct perturbation analysis for large imperfectly bound bimaterials containing small defects (Vellender et al., 2013); the absence of the square root singularity means that the weight functions are not used to find stress intensity factors, but instead yield asymptotic constants which describe the crack tip opening displacement. This quantity was proposed for use in fracture criteria by Wells (1961) and Cottrell (1962) and later justified rigorously by Rice and Sorenson (1978), Shih et al. (1979) and Kanninen et al. (1979). Despite their great utility, the derivation of such weight functions is often not straightforward and so the approach deployed in the remainder of this paper efficiently utilises existing relationships between known weight functions without the need to derive further expressions.

The paper is structured as follows: Section 2 introduces the problem geometry and model for the imperfect interface. In Section 3, previously found results used in the derivation of the singular integral equations are discussed. These include the weight functions derived using the method of Willis and Movchan (1995) and the Betti formula which can be used to relate the weight functions to the physical fields along both the crack and imperfect interface. Section 4 concentrates on solving the out-of-plane (mode III) problem. Singular integral equations are derived and used to obtain the displacement jump across both the crack and interface for a number of orthotropic bimaterials with varying levels of interface imperfection. Finite element methods for the same physical problems are also used to obtain the same results and then a comparison is made between the results obtained from the two opposing methods. The in-plane problem is considered in Section 5, where singular integral equations are once again obtained for the mode I and mode II tractions and displacements.

2. Problem formulation

We consider an infinite anisotropic bimaterial with an imperfect interface along the positive portion of the \(x_1\)-axis and a semi-infinite crack occupying the negative portion of the \(x_1\)-axis. The materials above and below the \(x_1\)-axis will be denoted materials I and II respectively.

The imperfect interface transmission conditions for \(x_1 > 0\) are given by

\[
t(x_1, 0^+) = t(x_1, 0^-),
\]

\[
u(x_1, 0^+) - \nu(x_1, 0^-) = \mathbf{K} t(x_1, 0^+),
\]

where \(\mathbf{t} = (t_1, t_2, t_3)^T\) is the traction vector and \(\mathbf{u} = (u_1, u_2, u_3)^T\) is the displacement vector. The matrix \(\mathbf{K}\) is an indication of the imperfection of the interface, with \(\mathbf{K} = 0\) corresponding to the perfect interface. For an anisotropic bonding material, \(\mathbf{K}\) has the following structure:

\[
\mathbf{K} = \begin{pmatrix}
K_{11} & K_{12} & 0 \\
K_{12} & K_{22} & 0 \\
0 & 0 & \kappa
\end{pmatrix}.
\]

The loading on the crack faces is considered known and given by

\[
t(x_1, 0^+) = \mathbf{p}^+(x_1), \quad t(x_1, 0^-) = \mathbf{p}^-(x_1) \quad \text{for } x_1 < 0.
\]
I

II

Figure 1: Geometry

The geometry considered is illustrated in Figure 1. The only restriction imposed on \( p^{\pm} \) is that they must be self-balanced; note in particular that this allows for discontinuous and/or asymmetric loadings. The symmetric and skew-symmetric parts of the loading are given by \( \langle p\rangle \) and \( [p] \) respectively, where the notation \( \langle f \rangle \) and \( [f] \) respectively denote the average and jump of the argument function:

\[
\langle f \rangle(x_1) = \frac{1}{2}(f(x_1,0^+) + f(x_1,0^-)), \quad [f](x_1) = f(x_1,0^+) - f(x_1,0^-).
\]

3. Application of existing weight functions

3.1. Weight functions

In the spirit of the efficiency outlined in the introduction section, we will introduce a method where integral identities involving the physical problem with an imperfect interface are found using the weight functions formulated in a perfect interface setting. The weight function used is the solution of the problem with the crack occupying the positive real \( x_1 \) axis with square-root singular displacement at the crack tip, as given in Morini et al. (2013b). The transmission conditions for the weight functions for \( x_1 < 0 \) are given as

\[
\Sigma(x_1,0^+) = \Sigma(x_1,0^-), \quad (5)
\]

\[
U(x_1,0^+) = U(x_1,0^-), \quad (6)
\]

where \( U \) is the singular displacement field and \( \Sigma \) is the corresponding traction field. Note in particular that condition (6) corresponds to a perfect interface weight function problem in contrast to the imperfect interface problem being physically considered.

It was shown in Morini et al. (2013b) that the following equations hold for the Fourier transforms of the symmetric and skew-symmetric parts of the weight function

\[
[U]^+(\xi) = \frac{1}{|\xi|} (\text{isign}(\xi)\text{Im}(H) - \text{Re}(H))\Sigma^-(\xi), \quad (7)
\]

\[
(U)(\xi) = \frac{1}{2|\xi|} (\text{isign}(\xi)\text{Im}(W) - \text{Re}(W))\Sigma^-(\xi), \quad (8)
\]

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where $\mathbf{H} = \mathbf{B}_I + \mathbf{B}_I^*$ and $\mathbf{W} = \mathbf{B}_I - \mathbf{B}_I^*$. Here, $\mathbf{B}_I$ and $\mathbf{B}_I^*$ are the surface admittance tensors of materials I and II respectively, superscript * denotes complex conjugation and bars denote Fourier transforms with respect to $x_1$ defined as

$$\tilde{f}(\xi) = \mathcal{F}[f](\xi) = \int_{-\infty}^{\infty} f(x_1)e^{i\xi x_1}dx_1.$$  \hfill (9)

The matrices $\mathbf{H}$ and $\mathbf{W}$ have the form

$$\mathbf{H} = \begin{pmatrix} H_{11} & -i\beta \sqrt{H_{11}H_{22}} & 0 \\ i\beta \sqrt{H_{11}H_{22}} & H_{22} & 0 \\ 0 & 0 & H_{33} \end{pmatrix}, \quad \mathbf{W} = \begin{pmatrix} \delta_1 H_{11} & i\gamma \sqrt{H_{11}H_{22}} & 0 \\ -i\gamma \sqrt{H_{11}H_{22}} & \delta_2 H_{22} & 0 \\ 0 & 0 & \delta_3 H_{33} \end{pmatrix}.$$  \hfill (10)

The entries of these matrices can be expressed in terms of the components of the material compliance tensors, $S$. Explicit expressions for $\mathbf{H}$ and $\mathbf{W}$ for orthotropic bimaterials are given in the Appendix of this paper.

### 3.2. Betti formula

In this section, the Betti formula is extended to the case of general asymmetrical loading applied at the crack surfaces. The Betti formula is used in order to relate the physical solution to the weight function, which is a special singular solution to the homogeneous problem with traction-free crack faces (Willis and Movchan 1995, Piccolroaz et al. 2007).

Applying the Betti formula to a semi-circular domain in the half-plane $x_2 > 0$, whose straight boundary is the line $x_2 = 0^+$, and whose radius $R \to \infty$, the following equation is obtained

$$\int_{\{x_2=0^+\}} \left\{ \mathcal{R} \mathbf{U}(x_1' - x_1,0^+) \cdot \mathbf{t}(x_1,0^+) - \mathcal{R} \mathbf{\Sigma}(x_1' - x_1,0^+) \cdot \mathbf{u}(x_1,0^+) \right\} dx_1 = 0.$$  \hfill (11)

where $\mathcal{R}$ is a rotation matrix given by

$$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}.$$  

Another equation can be derived by applying the Betti formula to a semi-circular domain in the half-plane $x_2 < 0$ and taking the limit, $R \to \infty$, which after some manipulation in the spirit of Piccolroaz et al. (2009) for example, yields

$$\mathcal{R} \mathbf{U} * (\mathbf{t})^{(+)} - \mathcal{R} (\mathbf{\Sigma})^{(-)} * [\mathbf{u}] = -\mathcal{R} \mathbf{U} * (\mathbf{p}) - \mathcal{R} (\mathbf{U}) * [\mathbf{p}],$$  \hfill (12)

where the convolutions are taken with respect to $x_1$, that is

$$(f * g)(x_1) = \int_{-\infty}^{\infty} f(x_1 - t)g(t)dt,$$

and superscripts $(\pm)$ denote the restriction of the preceding function to the respective semi-$x_1$-axis. Applying Fourier transforms then gives

$$[\mathbf{U}]^T \mathcal{R} (\mathbf{t})^{(+)} - ((\mathbf{\Sigma})^{-})^T \mathcal{R} [\mathbf{u}] = -[\mathbf{U}]^T \mathcal{R} (\mathbf{p}) - (\mathbf{U})^T \mathcal{R} [\mathbf{p}].$$  \hfill (13)

Note that the exact nature of the weight functions $\mathbf{U}$ and $\mathbf{\Sigma}$ used in this analysis have not been specified at this stage and so identity (13) is valid for a large class of weight functions. In particular, this allows for the use of perfect interface weight functions for the imperfect interface physical setting. In the case of perfect interface physical solution and weight functions, the corresponding analysis has been done in Piccolroaz and Mishuris (2013); Morini et al. (2013b), for isotropic and anisotropic materials respectively, while for imperfect interfaces joining isotropic bodies, details can be found in Mishuris et al. (2013).
4. Integral identities for mode III

4.1. Derivation of integral identities

We now seek boundary integral equations relating the mode III interfacial traction and displacement jump over the crack in the anisotropic bimaterial. This will utilise the Betti identity in order to relate the physical solution with the perfect interface weight functions.

Considering only the mode III components of [13] the following equation holds

\[
[U]\langle t \rangle^{(+)}(\xi) - \langle \Sigma \rangle^{(-)}(\xi)[u]\langle \xi \rangle = -[\hat{U}]\langle \xi \rangle \langle \hat{\rho} \rangle(\xi) - \langle U \rangle \langle \hat{p} \rangle(\xi),
\]

where the subscripts have been removed for notational brevity. Splitting \([U]\) into the sum of \([U]^{(\pm)}\) and also separating \([u]\) into the sum of \([u]^{(\pm)}\) gives

\[
[U]^{(+)}\langle t \rangle^{(+)}(\xi) + [U]^{(-)}\langle t \rangle^{(+)}(\xi) - \langle \Sigma \rangle^{(-)}(\xi)[u]^{(+)}(\xi) - \langle \Sigma \rangle^{(-)}(\xi)[u]^{(-)}(\xi) = -[\hat{U}]\langle \xi \rangle \langle \hat{\rho} \rangle(\xi) - \langle U \rangle \langle \hat{p} \rangle(\xi).
\]

Note that if imperfect interface weight functions are used, then the second and third terms of the left hand side of [15] immediately due to the transmission conditions [Vellender et al., 2013]. However, using perfect interface weight functions, this is not true.

Using the transmission conditions, \([U]^{(-)} = 0\) and \([u]^{(+)} = \kappa \langle t \rangle\), the following expression follows

\[
\langle t \rangle^{(+)} = -\left(\frac{\langle \Sigma \rangle^{(-)}}{[U]^{(+)}} \right) [u]^{(-)} = -\left(\frac{[U]}{[U]^{(+)}} - \kappa \langle \Sigma \rangle^{(-)}\right) \langle \hat{p} \rangle - \left(\frac{[U]}{[U]^{(+)}} - \kappa \langle \Sigma \rangle^{(-)}\right) \langle \hat{p} \rangle.
\]

From equations (7) and (8) the following relationships are seen to hold for the mode III components of the weight functions

\[
[U] = [U]^{(+)}(\xi) = \frac{H_{33}}{\kappa \xi} \langle \Sigma \rangle^{(-)}(\xi), \quad \langle U \rangle = \frac{\delta_{3}H_{33}}{2\xi} \langle \Sigma \rangle^{(-)}(\xi) = \frac{\delta_{3}}{2} [U](\xi);
\]

when combined with equation (16) the following relationship is obtained

\[
\langle t \rangle^{(+)} - A(\xi)[u]^{(-)} = -(1 + \kappa A(\xi)) \langle \hat{\rho} \rangle - \delta_{3} \left(1 + \kappa A(\xi)\right) [p]^{-},
\]

where

\[
A(\xi) = -\frac{|\xi|}{\kappa|\xi| + \kappa H_{33}}, \quad H_{33} = \frac{H_{33}}{\kappa}.
\]

Applying the inverse Fourier transform to equation (18) for the two cases, \(x_{1} < 0\) and \(x_{1} > 0\), the following relationships are obtained:

\[
F_{x_{1} < 0}^{-1} A(\xi)[u]^{(-)} = F_{x_{1} > 0}^{-1} \left(1 + \kappa A(\xi)\right) \langle \hat{\rho} \rangle + \frac{\delta_{3}}{2} F_{x_{1} < 0}^{-1} \left(1 + \kappa A(\xi)\right) [p]^{-},
\]

\[
\langle t \rangle^{(+)}(x_{1}) = F_{x_{1} > 0}^{-1} \left[A(\xi)[u]^{(-)}\right] - F_{x_{1} > 0}^{-1} \left[(1 + \kappa A(\xi)) \langle \hat{\rho} \rangle\right] - \frac{\delta_{3}}{2} F_{x_{1} > 0}^{-1} \left(1 + \kappa A(\xi)\right) [p]^{-}.
\]

To calculate these inversions the following relationships are used

\[
F^{-1} \left[A(\xi) \hat{f}(\xi)\right] = \frac{1}{\pi \kappa} \left(S_{H_{33}} * f'\right)(x_{1}),
\]

\[
F^{-1} \left[(1 + \kappa A(\xi)) \hat{f}(\xi)\right] = \frac{H_{33}}{\pi} \left(T_{H_{33}} * f\right)(x_{1}),
\]
and $\text{si}$ and $\text{ci}$ are the sine and cosine integral functions respectively, given by
\[ J_1(x) = \frac{\text{si}(\text{H}_{33}|x_1|)}{\text{H}_{33}|x_1|} - \text{sign}(x_1) \text{ci}(\text{H}_{33}|x_1|) \sin(\text{H}_{33}|x_1|), \]
\[ T_{\text{H}_{33}}(x_1) = \sin(\text{H}_{33}|x_1|) \sin(\text{H}_{33}|x_1|) - \text{ci}(\text{H}_{33}|x_1|) \cos(\text{H}_{33}|x_1|), \]
and $\text{si}$ and $\text{ci}$ are the sine and cosine integral functions respectively, given by
\[
\text{si}(x_1) = -\int_{x_1}^{\infty} \frac{\sin(t)}{t} dt, \quad \text{ci}(x_1) = -\int_{x_1}^{\infty} \frac{\cos(t)}{t} dt.
\]
These functions have the same properties as their counterparts from the isotropic case considered by Mishuris et al. (2013), but with different constants. In particular, the function $S_{\text{H}_{33}}(x_1)$ behaves as
\[ S_{\text{H}_{33}}(x_1) = \frac{\pi}{2} \text{sign}(x_1) + O(|x_1|), \quad x_1 \to 0, \quad S_{\text{H}_{33}}(x_1) = \frac{\text{sign}(x_1)}{\text{H}_{33}|x|} + O\left(\frac{1}{|x|^3}\right), \quad x_1 \to \pm \infty, \]
while $T_{\text{H}_{33}}(x_1)$ has behaviour of the form
\[ T_{\text{H}_{33}}(x_1) = \ln(|\text{H}_{33}|x_1|) + O(1), \quad x \to 0, \quad T_{\text{H}_{33}}(x_1) = -\frac{1}{\text{H}_{33}|x|^2} + O\left(\frac{1}{|x|^3}\right), \quad x \to \pm \infty. \]

We introduce convolution operators $S_{\text{H}_{33}}$ and $T_{\text{H}_{33}}$, as well as projection operators $P_{\pm}$:
\[ S_{\text{H}_{33}} \varphi(x_1) = (S_{\text{H}_{33}} \ast \varphi)(x_1), \quad T_{\text{H}_{33}} \varphi(x_1) = (T_{\text{H}_{33}} \ast \varphi)(x_1), \]
\[ P_{\pm} \varphi(x_1) = \begin{cases} \varphi(x_1) & \pm x_1 \geq 0, \\ 0 & \text{otherwise}, \end{cases} \]
in order to rewrite the identities (19) and (20) as
\[ \frac{1}{\pi \kappa} S_{\text{H}_{33}}^{(s)} \frac{\partial [u]^{(-)}(x_1)}{\partial x_1} - \frac{1}{\pi \kappa} [u]^{(-)}(0-) S_{\text{H}_{33}}(x_1) = -\frac{\text{H}_{33}}{\pi} T_{\text{H}_{33}}^{(s)}(p)(x_1) - \frac{\delta_3 \text{H}_{33}}{2\pi} T_{\text{H}_{33}}^{(s)}[p](x_1), \quad x_1 < 0, \]
\[ \langle t \rangle^{(+)}(x_1) = \frac{1}{\pi \kappa} \sigma_{\text{H}_{33}}^{(c)} \frac{\partial [u]^{(-)}(x_1)}{\partial x_1} - \frac{1}{\pi \kappa} [u]^{(-)}(0-) S_{\text{H}_{33}}(x_1) + \frac{\text{H}_{33}}{\pi} T_{\text{H}_{33}}^{(c)}(p)(x_1)
\]
\[ + \frac{\delta_3 \text{H}_{33}}{2\pi} T_{\text{H}_{33}}^{(c)}[p](x_1), \quad x_1 > 0, \]
where
\[ S_{\text{H}_{33}}^{(s)} = P_{-} S_{\text{H}_{33}} P_{-}, \quad T_{\text{H}_{33}}^{(s)} = P_{-} T_{\text{H}_{33}} P_{-}, \]
are singular operators and
\[ S_{\text{H}_{33}}^{(c)} = P_{+} S_{\text{H}_{33}} P_{-}, \quad T_{\text{H}_{33}}^{(c)} = P_{+} T_{\text{H}_{33}} P_{-}, \]
are compact. The second term on the left hand side of (30) and right hand side of (31) appear as a result of the discontinuity of the derivative of $[u]^{(-)}$ at $x_1 = 0$.

4.2. Alternative integral identities

The integral identities (30) and (31) can be formulated in alternative ways, yielding alternate integral identities which, depending upon the specific problem parameters and loadings, may aid the ease with which computations may be performed. Combining equations (21), (22) and (28) yields the following auxillary relationship
\[ -\frac{\text{H}_{33}}{\pi} T_{\text{H}_{33}} \varphi = T \varphi + \frac{1}{\pi} S_{\text{H}_{33}} \varphi'. \]
Using this relationship, equations (30) and (31) can be rewritten as follows

\[- \frac{\mathcal{H}_{33}}{\pi \kappa} \frac{\tau^{(s)}}{H_{33}} [u]^{(-)} - \frac{1}{\kappa} [u]^{(-)} = \frac{1}{\pi} \mathcal{S}_{H_{33}}^{(s)} \frac{\partial (p)}{\partial x_1} - \frac{1}{\pi} (p)(0^-) \mathcal{H}_{33} + [p] + \frac{\delta_3}{2 \pi} \mathcal{S}_{H_{33}}^{(c)} \frac{\partial [p]}{\partial x_1} + \frac{\delta_3}{2 \pi} [p](0^-) \mathcal{H}_{33} + \frac{\delta_3}{2} [p], \quad x_1 < 0,\]

\[\langle t \rangle^{(+)} = - \frac{\mathcal{H}_{33}}{\pi \kappa} \mathcal{T}_{H_{33}}^{(c)} [u]^{(-)} - \frac{1}{\kappa} [u]^{(-)} = \frac{1}{\pi} \mathcal{S}_{H_{33}}^{(c)} \frac{\partial (p)}{\partial x_1} + \frac{1}{\pi} (p)(0^-) \mathcal{H}_{33} + [p] - \frac{\delta_3}{2 \pi} \mathcal{S}_{H_{33}}^{(c)} \frac{\partial [p]}{\partial x_1} + \frac{\delta_3}{2 \pi} [p](0^-) \mathcal{H}_{33}, \quad x_1 > 0.\]

It is also possible to write these equations using only the operator \( \mathcal{T}_{H_{33}} \)

\[- \frac{\mathcal{H}_{33}}{\pi \kappa} \mathcal{T}_{H_{33}}^{(s)} [u]^{(-)} - \frac{1}{\kappa} [u]^{(-)} = - \frac{\mathcal{H}_{33}}{\pi \kappa} \mathcal{T}_{H_{33}}^{(s)} (p) + \frac{\delta_3}{2 \pi} \mathcal{H}_{33} \mathcal{T}_{H_{33}}^{(c)} [p], \quad x_1 < 0,\]

\[\langle t \rangle^{(+)} = - \frac{\mathcal{H}_{33}}{\pi \kappa} \mathcal{T}_{H_{33}}^{(c)} [u]^{(-)} + \frac{\mathcal{H}_{33}}{\pi \kappa} \mathcal{T}_{H_{33}}^{(c)} (p) + \frac{\delta_3}{2 \pi} \mathcal{H}_{33} \mathcal{T}_{H_{33}}^{(c)} [p], \quad x_1 > 0,\]

or alternatively solely the operator \( \mathcal{S}_{H_{33}} \)

\[\frac{1}{\pi \kappa} \mathcal{S}_{H_{33}}^{(s)} \frac{\partial [u]^{(-)}(0^-)}{\partial x_1} - \frac{1}{\pi \kappa} [u]^{(-)}(0^-) \mathcal{S}_{H_{33}} = \]

\[\frac{1}{\pi \kappa} \mathcal{S}_{H_{33}}^{(c)} \frac{\partial (p)}{\partial x_1} - \frac{1}{\pi \kappa} (p)(0^-) \mathcal{S}_{H_{33}} + [p] + \frac{\delta_3}{2 \pi} \mathcal{S}_{H_{33}}^{(c)} \frac{\partial [p]}{\partial x_1} - \frac{\delta_3}{2 \pi} [p](0^-) \mathcal{S}_{H_{33}} + \frac{\delta_3}{2} [p], \quad x_1 < 0,\]

\[\langle t \rangle^{(+)} = \frac{1}{\pi \kappa} \mathcal{S}_{H_{33}}^{(c)} \frac{\partial [u]^{(-)}(0^-)}{\partial x_1} - \frac{1}{\pi \kappa} [u]^{(-)}(0^-) \mathcal{S}_{H_{33}} = \]

\[- \frac{1}{\pi \kappa} \mathcal{S}_{H_{33}}^{(c)} \frac{\partial (p)}{\partial x_1} + \frac{1}{\pi \kappa} (p)(0^-) \mathcal{S}_{H_{33}} + [p] - \frac{\delta_3}{2 \pi} \mathcal{S}_{H_{33}}^{(c)} \frac{\partial [p]}{\partial x_1} + \frac{\delta_3}{2 \pi} [p](0^-) \mathcal{S}_{H_{33}}, \quad x_1 > 0.\]

Each of the four formulations have advantages for numerical computations depending on which boundary conditions are known and the desired results. The merits of each formulation for the analogous isotropic case have been discussed in detail in [Mishuris et al. (2013)] and we refer the reader to that paper for further discussion.

4.3. Numerical results
4.3.1. Results from singular integral equations

In this section, the integral identities found previously will be used to calculate the jump in displacement over the crack and imperfect interface between two orthotropic materials. Results for finite element simulations using COMSOL will also be presented and compared to the results using the integral identity approach derived in the previous subsection.

For orthotropic materials, the material parameters \( H_{33} \) and \( \delta_3 \) are given in terms of the components of the material compliance tensor, \( \mathbf{S} \), in the Appendix of the paper. It is possible to express \( S_{44} \) and \( S_{55} \) in terms of the shear moduli, \( \mu_{ij} \), of the material

\[ S_{44} = \frac{1}{\mu_{23}}, \quad S_{55} = \frac{1}{\mu_{13}}. \]
Table 1: Material properties

| Orientation | $\mu_{23}$ | $\mu_{13}$ | $\mu_{12}$ |
|-------------|------------|------------|------------|
| A           | 1          | 2/3        | 1/2        |
| B           | 1          | 1/2        | 2/3        |
| C           | 1/2        | 2/3        | 1          |

considered are shown in Table 1. The values of $\mu_{12}$ are given in Table 1 to illustrate that the materials considered are the same but differently oriented. Henceforth, the material above the crack, I, will always be A from Table I.

We first consider a symmetric distribution of loadings given by

$$[p](x_1) = 0, \quad \langle p \rangle(x_1) = -\frac{F}{l} e^{x_1}. \quad (42)$$

Figure 2 plots the normalised displacement jump along the $x_1$-axis induced by the above loading for the three possible orientations for material II for two different degrees of interface imperfection which have been computed by numerically solving the integral equations (37) and (38) using an iterative scheme in Mathematica. The normalised displacement jump is denoted $[u^*]$ and defined by

$$[u^*] = \frac{1}{F} \left[ \sqrt{S_{44} S_{55}} \right]_l [u]. \quad (43)$$

A normalised traction, $t^*$, is also used in the calculations and is related to the normalised displacement jump by the relationship: $[u^*] = \kappa^* t^*$, where

$$t^* = \frac{l}{F} t, \quad \kappa^* = \frac{1}{l} \left[ \sqrt{S_{44} S_{55}} \right]_l \kappa. \quad (44)$$

Figure 2: Graph of normalised displacement jump over the crack and interface induced by loading (42).
The graph shown in Figure 2 shows that a higher value of $\kappa$ gives a higher jump in displacement across the crack and interface for all orientations of the bottom material. This result is expected as a larger $\kappa$ refers to a less stiff interface. It is also seen that for the same value of $\kappa$, the orientation of the anisotropy has a diminishing effect along the interface ($x_1 > 0$) as the distance from the crack tip is increased.

The difference in orientation of material II has a clear effect on the jumps in displacement shown in Figure 2, with the same behaviour observed for both values of $\kappa$ studied here. The highest jump in both cases is seen for orientation C in the lower half-plane. This is due to the lower shear moduli contributing to the mode-III fields in this case. The lower differences in displacement occur when orientation A is considered below the interface; caused by higher shear moduli in the out-of-plane direction.

In order to demonstrate that the method is applicable for asymmetric as well as symmetric loadings, we present in Figure 3 a similar plot, but instead using asymmetric loadings of the form

$$p^+(x_1) = -\frac{F}{l} x_1 e^{x_1/l}, \quad p^-(x_1) = \frac{F}{l^2} x_1 e^{x_1/l}. \quad (45)$$

![Figure 3: Displacement jump for asymmetric loading.](image)

4.3.2. Finite element results

This part of the paper considers finite element simulations performed in COMSOL for a crack along an imperfect interface. When using COMSOL it is not possible to implement the transmission conditions (1) and (2) across the interface. Instead, a very thin layer of a softer material is used for the interface and the properties of that material are varied to obtain the desired value for $\kappa$ (see for instance Antipov et al. (2001)). Also, it is not possible to have an infinite geometry in COMSOL and therefore a very large, finite geometry is used in order to get results similar to an infinite geometry near the crack tip. An example colour map of the Mode-III displacement from COMSOL is shown in Figure 4 using material orientation A for both main material bodies and an interface layer corresponding to $\kappa = 20$.

Using the displacement fields found using COMSOL, a value for the displacement jump over the crack and interface have been found for a number of points near the crack tip for two of the examples shown in Figure 2. The examples chosen were $\kappa = 20$ with material II having orientation C and $\kappa = 5$ with both materials above and below the crack having the same properties in the same directions. The results of these comparisons are shown in Figure 5 and Table 2.
Figure 4: Finite element computations of displacement jump, using a thin densely-meshed soft layer in place of the imperfect interface.

| Material | -5  | -4  | -3  | -2  | -1  | 0   | 1   | 2   | 3   | 4   | 5   |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| A, \( \kappa = 5 \) | 2.30 | 1.81 | 1.07 | 0.61 | 0.20 | 0.06 | 0.18 | 0.70 | 3.41 | 2.77 | 4.66 |
| C, \( \kappa = 20 \) | 0.53 | 0.62 | 0.84 | 0.87 | 1.13 | 0.55 | 1.80 | 2.75 | 3.81 | 5.19 | 6.70 |

Table 2: Percentage difference between Mathematica and COMSOL.

The results shown in Figure 5 show a good agreement between the results from the singular integral equations and those obtained from finite element methods. The difference in results is smallest at the crack tip but more error can be seen at a further distance along both the crack and interface, which is emphasised by the larger percentage errors shown in Table 2. This is likely caused by the finite geometry that was used in COMSOL which leads to an influence caused by the outer boundaries.

5. Integral identities for mode I and II

Heretofore, we have derived integral identities for the mode III regime only. This section seeks to find boundary integral equations relating the mode I and II interfacial traction and displacement jump over the crack in an imperfectly bound anisotropic bimaterial. For the mode I and II components the following equation holds

\[ [U]^T \mathcal{R}(t) - \langle \Sigma \rangle^{(-)}^T \mathcal{R}[u] = -[U]^T \mathcal{R}(p) - \langle U \rangle^T \mathcal{R}[p]. \]  

(46)

The matrices and vectors shown here contain only the mode I and II components from (13). The 2x2 matrices \( \dot{U} \) and \( \Sigma \) consist of two linearly independent weight functions (Piccolroaz et al., 2009).

Splitting \( [U] \) into the sum of \( [U]^{(\pm)} \) and \( [u] \) into \( [u]^{(\pm)} \), where (as previously) superscripts \((\pm)\) denote
the restriction of the preceding function to the respective semi-\(x_1\)-axis, gives

\[
\begin{align*}
\Bigl[\mathbf{U}\Bigr]^{(\mp)} \mathcal{R}(t)^{(\mp)} + \Bigl[\mathbf{U}\Bigr]^{(-)} \mathcal{R}(t)^{(+) - (\Sigma)}^{(-)} \mathcal{R}[\mathbf{u}]^{(+)} - (\Sigma)^{(-)} \mathcal{R}[\mathbf{u}]^{(-)} \\
= - \Bigl[\mathbf{U}\Bigr]^{(\mp)} \mathcal{R}(\mathbf{\bar{p}}) - \langle \mathbf{U} \rangle^{(\mp)} \mathcal{R}[\mathbf{\bar{p}}].
\end{align*}
\]

(47)

Applying the boundary conditions, \(\mathbf{U}^{(-)} = 0\) and \(\mathbf{u}^{(+)} = \mathbf{K}(t)^{(+) - (\Sigma)}^{(-)} \mathcal{R}[\mathbf{u}]^{(-)}\), along with equations (7) and (8) gives the following expression

\[
\langle t \rangle^{(+) - (\Sigma)} = \frac{1}{2} \mathcal{R}^{-1}((\xi | K^* + R_H - \text{isign}(\xi) I_H - \text{isign}(\xi) I_W)^T R_W - \text{isign}(\xi) I_W)^T \mathcal{R},
\]

\[
B(\xi) = - i \mathcal{R}^{-1}(\xi K^* + \text{sign}(\xi) R_H - i I_H)^{-T} \mathcal{R},
\]

\[
C(\xi) = \mathcal{R}^{-1}((\xi | K^* + R_H - \text{isign}(\xi) I_H)^{-T} (R_H - \text{isign}(\xi) I_H)^T \mathcal{R}.
\]

Here, \(R_H = \text{Re}(H), R_W = \text{Re}(W), I_H = \text{Im}(H), I_W = \text{Im}(W)\) and \(K^* = \mathcal{R} K \mathcal{R}\). Full expressions for matrices \(A(\xi), B(\xi)\) and \(C(\xi)\) can be found in the appendix of this paper.

Applying the inverse Fourier transform to equation (48) for the two cases, \(x_1 < 0\) and \(x_1 > 0\), the following relationships are obtained:

\[
\mathcal{F}_{x_1 < 0}^{-1} \left[ B(\xi) \frac{\xi}{i} \mathbf{u}\right]^{(\mp)} = \mathcal{F}_{x_1 < 0}^{-1} \left[ C(\xi) \mathbf{\bar{p}}\right] + \mathcal{F}_{x_1 < 0}^{-1} \left[ A(\xi) \mathbf{\bar{p}}\right],
\]

(49)

\[
\langle t \rangle(x_1) = \mathcal{F}_{x_1 > 0}^{-1} \left[ B(\xi) \frac{\xi}{i} \mathbf{u}\right]^{(-)} - \mathcal{F}_{x_1 > 0}^{-1} \left[ C(\xi) \mathbf{\bar{p}}\right] - \mathcal{F}_{x_1 > 0}^{-1} \left[ A(\xi) \mathbf{\bar{p}}\right].
\]

(50)
The inverse Fourier transforms of the matrices $A(\xi)$, $B(\xi)$, and $C(\xi)$ are derived in the appendix of this paper. The singular integral equations obtained for the in-plane fields are thus

$$
B^{(s)} \left( \frac{\partial [u]^{-}}{\partial x_1} \right) + \frac{1}{\pi d_2 (\xi_2 - \xi_1)} \sum_{j=1}^{2} B^{(j)}_R T^{(s,c)}_{\xi_j}(x_1) [u]^{-} - \frac{1}{\pi d_2 (\xi_2 - \xi_1)} \sum_{j=1}^{2} B^{(j)}_R S^{(s,c)}_{\xi_j}(x_1) [u]^{-} = C^{(s)}(p)(x_1) + A^{(s)}[p](x_1), \text{ for } x_1 < 0, \tag{51}
$$

$$
(t)(x_1) = B^{(c)} \left( \frac{\partial [u]^{-}}{\partial x_1} \right) + \frac{1}{\pi d_2 (\xi_2 - \xi_1)} \sum_{j=1}^{2} B^{(j)}_R T^{(c)}_{\xi_j}(x_1) [u]^{-} - C^{(c)}(p)(x_1) - A^{(c)}[p](x_1), \text{ for } x_1 > 0. \tag{52}
$$

The operators used in equations (51) and (52) are given by

$$
A^{(s,c)} = -\frac{1}{2\pi d_2 (\xi_2 - \xi_1)} \left\{ \sum_{j=1}^{2} A^{(j)}_R T^{(s,c)}_{\xi_j}(x_1) + \sum_{j=1}^{2} A^{(j)}_I S^{(s,c)}_{\xi_j}(x_1) \right\}, \tag{53}
$$

$$
B^{(s,c)} = -\frac{1}{\pi d_2 (\xi_2 - \xi_1)} \left\{ \sum_{j=1}^{2} B^{(j)}_R T^{(s,c)}_{\xi_j}(x_1) + \sum_{j=1}^{2} B^{(j)}_I S^{(s,c)}_{\xi_j}(x_1) \right\}, \tag{54}
$$

$$
C^{(s,c)} = -\frac{1}{\pi d_2 (\xi_2 - \xi_1)} \left\{ \sum_{j=1}^{2} C^{(j)}_R T^{(s,c)}_{\xi_j}(x_1) + \sum_{j=1}^{2} C^{(j)}_I S^{(s,c)}_{\xi_j}(x_1) \right\}. \tag{55}
$$

6. Conclusions

Singular integral equations have been derived which relate the loading on crack faces to the consequent crack opening displacement and interfacial tractions for a semi-infinite crack situated along a soft anisotropic imperfect interface for an anisotropic bimaterial. The derivation made efficient use of perfect interface weight functions applied to an imperfect interface physical problem; this did not require derivation of new weight functions. As in the previously studied analogous isotropic problem, the imperfect interface’s presence causes a logarithmic singularity in the kernel of the integral operator. Alternative formulations have been presented for the mode III case and used to perform computations for orthotropic materials, which display a good degree of accuracy when compared against finite element simulations.

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Appendix A. Bimaterial matrices \( H \) and \( W \) for orthotropic bimaterials

The matrices \( H \) and \( W \) have the form

\[
H = \begin{pmatrix}
H_{11} & -i\beta H_{11}H_{22} & 0 \\
i\beta H_{11}H_{22} & H_{22} & 0 \\
0 & 0 & H_{33}
\end{pmatrix}, \quad W = \begin{pmatrix}
\delta_1 H_{11} & i\gamma H_{11}H_{22} & 0 \\
-\gamma H_{11}H_{22} & \delta_2 H_{22} & 0 \\
0 & 0 & \delta_3 H_{33}
\end{pmatrix}.
\] (A.1)

For orthotropic materials it is possible to obtain explicit expressions for the these matrices in terms of the components of the material compliance tensors.

The out-of-plane components are given by

\[
H_{33} = \left[ \sqrt{S_{44}S_{55}} \right]_{II} + \left[ \sqrt{S_{44}S_{55}} \right]_{II}, \quad \delta_3 = \left[ \sqrt{S_{44}S_{55}} \right]_{I} - \left[ \sqrt{S_{44}S_{55}} \right]_{II},
\] (A.2)

The in-plane components of \( H \) can be found in Morini et al. (2013b) and are given as

\[
H_{11} = \left[ 2n\lambda^{1/4} \sqrt{S_{11}S_{22}} \right]_I + \left[ 2n\lambda^{1/4} \sqrt{S_{11}S_{22}} \right]_{II},
\] (A.3)

\[
H_{22} = \left[ 2n\lambda^{-1/4} \sqrt{S_{11}S_{22}} \right]_I + \left[ 2n\lambda^{-1/4} \sqrt{S_{11}S_{22}} \right]_{II},
\] (A.4)

\[
\beta = \frac{[S_{12} + \sqrt{S_{11}S_{22}}]_I}{\sqrt{H_{11}H_{22}}}, \quad \gamma = \frac{[S_{12} + \sqrt{S_{11}S_{22}}]_II}{\sqrt{H_{11}H_{22}}},
\] (A.5)

where

\[
\lambda = \frac{S_{11}}{S_{22}}, \quad n = \sqrt{(1+\rho)/2}, \quad \rho = \frac{2S_{12} + S_{66}}{2\sqrt{S_{11}S_{22}}}
\]

The in-plane components of \( W \) were also given in Morini et al. (2013b):

\[
\delta_1 = \left[ 2n\lambda^{1/4} \sqrt{S_{11}S_{22}} \right]_I - \left[ 2n\lambda^{1/4} \sqrt{S_{11}S_{22}} \right]_{II},
\] (A.6)

\[
\delta_2 = \left[ 2n\lambda^{-1/4} \sqrt{S_{11}S_{22}} \right]_I - \left[ 2n\lambda^{-1/4} \sqrt{S_{11}S_{22}} \right]_{II},
\] (A.7)

\[
\gamma = \frac{[S_{12} + \sqrt{S_{11}S_{22}}]_I + [S_{12} + \sqrt{S_{11}S_{22}}]_{II}}{\sqrt{H_{11}H_{22}}},
\] (A.8)

Appendix B. The matrices \( A(\xi), B(\xi) \) and \( C(\xi) \)

Matrices \( A(\xi), B(\xi) \) and \( C(\xi) \) have the following form

\[
A(\xi) = \frac{1}{2D} \begin{pmatrix} A_{11} & A_{21} \\ A_{21} & A_{22} \end{pmatrix}, \quad B(\xi) = \frac{1}{D} \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}, \quad C(\xi) = \frac{1}{D} \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix}
\] (B.1)

where the denominator \( D \) is defined as

\[
D = d_0 + d_1 |\xi| + d_2 |\xi|^2,
\] (B.2)

\[
d_0 = H_{11}H_{22}(1-\beta^2), \quad d_1 = K_{11}H_{22} + K_{22}H_{11}, \quad d_2 = K_{11}K_{22} - K_{12}^2,
\]

and the elements \( A_{ij}, B_{ij}, C_{ij} \) are given by

\[
A_{11} = H_{11}H_{22}(\delta_1 + \beta\gamma) + |\xi|(\delta_1H_{11}K_{22} - i\gamma K_{12}\sqrt{H_{11}H_{22}} \text{ sign}(\xi)),
\]

\
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\[ A_{12} = -i \sign(\xi) H_{22} \sqrt{H_{11} H_{22}} (\gamma + \beta \delta_2) - |\xi|(i \gamma K_{22} \sqrt{H_{11} H_{22}} \sign(\xi) + \delta_2 H_{22} K_{12}) , \]
\[ A_{21} = i \sign(\xi) H_{11} \sqrt{H_{11} H_{22}} (\delta_1 \beta + \gamma) - |\xi|(\delta_1 H_{11} K_{12} - i \gamma K_{11} \sqrt{H_{11} H_{22}} \sign(\xi)), \]
\[ A_{22} = H_{11} H_{22} (\beta \gamma + \delta_2) + |\xi|(\delta_2 H_{22} K_{11} + i \gamma K_{12} \sqrt{H_{11} H_{22}} \sign(\xi)), \]
\[
B_{11} = -i(\xi K_{22} + H_{22} \sign(\xi)), \quad B_{12} = i \xi K_{12} - \beta \sqrt{H_{11} H_{22}}, \quad B_{21} = i \xi K_{12} + \beta \sqrt{H_{11} H_{22}}, \quad B_{22} = -i(\xi K_{11} + H_{11} \sign(\xi)), \]
\[
C_{11} = H_{11} H_{22}(1 - \beta^2) + |\xi|(H_{11} K_{22} + i \beta K_{12} \sqrt{H_{11} H_{22}} \sign(\xi)), \quad C_{12} = -|\xi|(H_{22} K_{12} - i \beta \sign(\xi) K_{22} \sqrt{H_{11} H_{22}}), \quad C_{21} = -|\xi|(H_{11} K_{12} + i \beta \sign(\xi) K_{11} \sqrt{H_{11} H_{22}}), \quad C_{22} = H_{11} H_{22}(1 - \beta^2) + |\xi|(H_{22} K_{11} - i \beta K_{12} \sqrt{H_{11} H_{22}} \sign(\xi)).
\]

\section*{Appendix C. Inverse Fourier transforms of matrices A(\xi), B(\xi) and C(\xi)}

\subsection*{Appendix C.1. General procedure}

The method outlined in [Mishuris et al. (2013)] is used in order to perform the Fourier inversion of the matrices A(\xi), B(\xi) and C(\xi). The denominator D defined in (B.2) is factorised in the following manner
\[
D = d_2(|\xi| + \xi_1)(|\xi| + \xi_2),
\]
where
\[
\xi_{1,2} = \frac{d_1 \mp \sqrt{d_1^2 - 4d_2d_0}}{2d_2} > 0,
\]
The typical term to invert is of the form
\[
F(\xi) = \frac{F_R + F_R^\dagger \xi}{D} + i \frac{F_I \sign(\xi) + F_I^\dagger \xi}{D},
\]
The function F has the following property
\[
F(-\xi) = F(\bar{\xi}),
\]
therefore, the Fourier inversion can be obtained as
\[
\mathcal{F}^{-1}[F(\xi)] = \frac{1}{\pi} \Re \int_0^{\infty} F(\xi) e^{-i \xi x} d\xi = \frac{1}{\pi} \int_0^{\infty} \Re[F(\xi)] \cos(x \xi) d\xi + \frac{1}{\pi} \int_0^{\infty} \Im[F(\xi)] \sin(x \xi) d\xi,
\]
where for \( \xi > 0 \)
\[
\Re[F(\xi)] = \frac{F_R + F_R^\dagger \xi}{D} = \sum_{j=1}^{2} \frac{F_R^{(j)}}{d_2(\xi_2 - \xi_1)(\xi + \xi_j)},
\]
\[
\Im[F(\xi)] = \frac{F_I + F_I^\dagger \xi}{D} = \sum_{j=1}^{2} \frac{F_I^{(j)}}{d_2(\xi_2 - \xi_1)(\xi + \xi_j)},
\]

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and
\[ F_{R,I}^{(1)} = F_{R,I} - F_{R,I}^\dagger \xi_1, \quad F_{R,I}^{(2)} = -F_{R,I} + F_{R,I}^\dagger \xi_2. \]  
(C.8)

The following formulae can now be used

\[
\int_0^\infty \text{Re}[F(\xi)] \cos(x_1 \xi) d\xi = \frac{2}{d_2(\xi_2 - \xi_1)} \int_0^\infty \cos(x_1 \xi) d\xi = -\frac{1}{d_2(\xi_2 - \xi_1)} \sum_{j=1}^2 F^{(j)}_{R} T_{\xi_j}(x_1), \quad \tag{C.9}
\]

\[
\int_0^\infty \text{Im}[F(\xi)] \sin(x_1 \xi) d\xi = \frac{2}{d_2(\xi_2 - \xi_1)} \int_0^\infty \sin(x_1 \xi) d\xi = -\frac{1}{d_2(\xi_2 - \xi_1)} \sum_{j=1}^2 F^{(j)}_{I} S_{\xi_j}(x_1), \quad \tag{C.10}
\]

where functions \( S_{\xi_j}(x) \) and \( T_{\xi_j}(x) \) are defined as in (23) and (24), respectively.

Finally the Fourier inversion of the general term \( F(\xi) \) as given as

\[
\mathcal{F}^{-1}[F(\xi)] = -\frac{1}{2\pi d_2(\xi_2 - \xi_1)} \left\{ \sum_{j=1}^2 F^{(j)}_{R} T_{\xi_j}(x_1) + \sum_{j=1}^2 F^{(j)}_{I} S_{\xi_j}(x_1) \right\}. \quad \tag{C.11}
\]

Appendix C.2. Fourier inversion of \( \mathbf{A}(\xi) \).

For \( \xi > 0 \), \( \mathbf{A}(\xi) \) can be written as

\[
\mathbf{A}(\xi) = \frac{1}{2D}(\mathbf{A}_R + \mathbf{A}_R^\dagger \xi) + \frac{i}{2D}(\mathbf{A}_I + \mathbf{A}_I^\dagger \xi) = \frac{1}{2d_2(\xi_2 - \xi_1)} \left\{ \sum_{j=1}^2 \frac{1}{\xi + \xi_j} \mathbf{A}^{(j)}_R + i \sum_{j=1}^2 \frac{1}{\xi + \xi_j} \mathbf{A}^{(j)}_I \right\}, \quad \tag{C.12}
\]

where

\[
\mathbf{A}_R = H_{11} H_{22} \begin{pmatrix} \delta_1 + \beta \gamma & 0 \\ 0 & \delta_2 + \beta \gamma \end{pmatrix}, \quad \mathbf{A}_R^\dagger = \begin{pmatrix} \delta_1 H_{11} K_{22} & -\delta_2 H_{22} K_{12} \\ -\delta_1 H_{11} K_{12} & \delta_2 H_{22} K_{11} \end{pmatrix}, \quad \tag{C.13}
\]

\[
\mathbf{A}_I = \sqrt{H_{11} H_{22}} \begin{pmatrix} 0 & -H_{22}(\delta_2 \beta + \gamma) \\ H_{11}(\delta_1 \beta + \gamma) & 0 \end{pmatrix}, \quad \mathbf{A}_I^\dagger = \gamma \sqrt{H_{11} H_{22}} \begin{pmatrix} -K_{12} & -K_{22} \\ K_{11} & K_{22} \end{pmatrix}, \quad \tag{C.14}
\]

\[
\mathbf{A}^{(1)}_R = \mathbf{A}_R - \mathbf{A}_R^\dagger \xi_1 = \begin{pmatrix} \delta_1 H_{22}(\delta_1 + \beta \gamma) - \delta_1 K_{22} \xi_1 \\ \delta_1 H_{11} K_{12} \xi_1 \end{pmatrix}, \quad \mathbf{A}^{(2)}_R = \mathbf{A}_R - \mathbf{A}_R^\dagger \xi_2 = \begin{pmatrix} -\delta_1 H_{22} K_{12} \xi_2 \\ -\delta_2 H_{22} K_{12} \xi_2 \end{pmatrix}, \quad \tag{C.15}
\]

\[
\mathbf{A}^{(1)}_I = \mathbf{A}_I - \mathbf{A}_I^\dagger \xi_1 = \sqrt{H_{11} H_{22}} \begin{pmatrix} \delta_1 H_{11} K_{12} \xi_1 \\ -H_{11}(\delta_1 \beta + \gamma) - \gamma K_{11} \xi_1 \end{pmatrix}, \quad \mathbf{A}^{(2)}_I = \mathbf{A}_I - \mathbf{A}_I^\dagger \xi_2 = \sqrt{H_{11} H_{22}} \begin{pmatrix} -\gamma K_{12} \xi_2 \\ -H_{11}(\delta_1 \beta + \gamma) + \gamma K_{11} \xi_2 \end{pmatrix}. \quad \tag{C.16}
\]

The Fourier inverse of the matrix \( \mathbf{A}(\xi) \) is given by

\[
\mathcal{F}^{-1}[\mathbf{A}(\xi)] = -\frac{1}{2\pi d_2(\xi_2 - \xi_1)} \left\{ \sum_{j=1}^2 \mathbf{A}^{(j)}_R T_{\xi_j}(x_1) + \sum_{j=1}^2 \mathbf{A}^{(j)}_I S_{\xi_j}(x_1) \right\}. \quad \tag{C.19}
\]
Appendix C.3. Fourier inversion of the matrix \( \mathbf{B}(\xi) \).

For \( \xi > 0 \) \( \mathbf{B}(\xi) \) can be written as

\[
\mathbf{B}(\xi) = \frac{1}{D}(\mathbf{B}_R + \mathbf{B}_R \xi) + \frac{i}{D}(\mathbf{B}_I + \mathbf{B}_I \xi) = \frac{1}{d_2(\xi_2 - \xi_1)} \left\{ \sum_{j=1}^{2} \frac{1}{\xi + \xi_j} \mathbf{B}_R^{(j)} + i \sum_{j=1}^{2} \frac{1}{\xi + \xi_j} \mathbf{B}_I^{(j)} \right\},
\]

where

\[
\mathbf{B}_R = \beta \sqrt{H_{11}H_{22}} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad \mathbf{B}_I = \begin{pmatrix} -H_{22} & 0 \\ 0 & -H_{11} \end{pmatrix},
\]

\[
\frac{1}{\xi + \xi_j} \mathbf{B}_R^{(j)} = \begin{pmatrix} -K_{22} & K_{12} \\ K_{12} & -K_{11} \end{pmatrix},
\]

\[
\frac{1}{\xi + \xi_j} \mathbf{B}_I^{(j)} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix},
\]

\[
\mathbf{B}_R^{(1)} = \mathbf{B}_R - \mathbf{B}_R^\dagger \xi_1 = \beta \sqrt{H_{11}H_{22}} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix},
\]

\[
\mathbf{B}_R^{(2)} = -\mathbf{B}_R + \mathbf{B}_R^\dagger \xi_2 = \beta \sqrt{H_{11}H_{22}} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix},
\]

\[
\mathbf{B}_I^{(1)} = \mathbf{B}_I - \mathbf{B}_I^\dagger \xi_1 = \begin{pmatrix} -H_{22} + K_{22} \xi_1 & -K_{12} \xi_1 \\ -K_{12} \xi_1 & -H_{11} + K_{11} \xi_1 \end{pmatrix},
\]

\[
\mathbf{B}_I^{(2)} = -\mathbf{B}_I + \mathbf{B}_I^\dagger \xi_2 = \begin{pmatrix} H_{22} - K_{22} \xi_2 & K_{12} \xi_2 \\ K_{12} \xi_2 & H_{11} - K_{11} \xi_2 \end{pmatrix}.
\]

The Fourier inverse of the matrix \( \mathbf{B}(\xi) \) is then

\[
\mathcal{F}^{-1}[\mathbf{B}(\xi)] = -\frac{1}{\pi d_2(\xi_2 - \xi_1)} \left\{ \sum_{j=1}^{2} \frac{1}{\xi + \xi_j} \mathbf{B}_R^{(j)} T_{\xi_j}(x_1) + \sum_{j=1}^{2} \frac{1}{\xi + \xi_j} \mathbf{B}_I^{(j)} S_{\xi_j}(x_1) \right\}.
\]

Appendix C.4. Fourier inversion of the matrix \( \mathbf{C}(\xi) \).

For \( \xi > 0 \) \( \mathbf{C}(\xi) \) can be written as

\[
\mathbf{C}(\xi) = \frac{1}{D}(\mathbf{C}_R + \mathbf{C}_R^\dagger \xi) + \frac{i}{D}(\mathbf{C}_I + \mathbf{C}_I^\dagger \xi) = \frac{1}{d_2(\xi_2 - \xi_1)} \left\{ \sum_{j=1}^{2} \frac{1}{\xi + \xi_j} \mathbf{C}_R^{(j)} + i \sum_{j=1}^{2} \frac{1}{\xi + \xi_j} \mathbf{C}_I^{(j)} \right\},
\]

where

\[
\mathbf{C}_R = \begin{pmatrix} H_{11}H_{22}(1 - \beta^2) & 0 \\ 0 & H_{11}H_{22}(1 - \beta^2) \end{pmatrix}, \quad \mathbf{C}_R^\dagger = \begin{pmatrix} H_{11}K_{22} & -H_{22}K_{12} \\ -H_{11}K_{12} & H_{22}K_{11} \end{pmatrix},
\]

\[
\frac{1}{\xi + \xi_j} \mathbf{C}_R^{(j)} = \begin{pmatrix} K_{12} & K_{22} \\ -K_{11} & -K_{12} \end{pmatrix},
\]

\[
\frac{1}{\xi + \xi_j} \mathbf{C}_I^{(j)} = \begin{pmatrix} H_{11}(H_{22}(1 - \beta^2) - K_{22} \xi_1) & H_{22}K_{12} \xi_1 \\ H_{11}K_{12} \xi_1 & H_{22}(H_{11}(1 - \beta^2) - K_{11} \xi_1) \end{pmatrix},
\]

\[
\frac{1}{\xi + \xi_j} \mathbf{C}_R^{(1)} = \mathbf{C}_R - \mathbf{C}_R^\dagger \xi_1 = \begin{pmatrix} H_{11}(H_{22}(1 - \beta^2) - K_{22} \xi_1) & H_{22}K_{12} \xi_1 \\ H_{11}K_{12} \xi_1 & H_{22}(H_{11}(1 - \beta^2) - K_{11} \xi_1) \end{pmatrix},
\]

\[
\frac{1}{\xi + \xi_j} \mathbf{C}_R^{(2)} = -\mathbf{C}_R + \mathbf{C}_R^\dagger \xi_2 = \begin{pmatrix} -H_{11}(H_{22}(1 - \beta^2) - K_{22} \xi_2) & -H_{22}K_{12} \xi_2 \\ -H_{11}K_{12} \xi_2 & -H_{22}(H_{11}(1 - \beta^2) - K_{11} \xi_2) \end{pmatrix},
\]

\[
\frac{1}{\xi + \xi_j} \mathbf{C}_I^{(1)} = \mathbf{C}_I - \mathbf{C}_I^\dagger \xi_1 = \beta \sqrt{H_{11}H_{22}} \begin{pmatrix} -K_{12} & -K_{22} \\ K_{11} & K_{12} \end{pmatrix},
\]

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\[ \mathbf{C}_I^{(2)} = -\mathbf{C}_I + \mathbf{C}_I^\dagger \xi_2 = -\beta \sqrt{H_{11} H_{22}} \xi_2 \begin{pmatrix} -K_{12} & -K_{22} \\ K_{11} & K_{12} \end{pmatrix}. \] (C.34)

The Fourier inverse of the matrix \( \mathbf{C}(\xi) \) is then

\[ \mathcal{F}^{-1}[\mathbf{C}(\xi)] = -\frac{1}{2 \pi d_2 (\xi_2 - \xi_1)} \left\{ \sum_{j=1}^{2} \mathbf{C}_R^{(j)} T_{\xi_j}(x_1) + \sum_{j=1}^{2} \mathbf{C}_I^{(j)} S_{\xi_j}(x_1) \right\}. \] (C.35)