



AD FALCON API Manual

# Analysis of Plane Strain Foundation Using Orthotropic Elastic Material

Javad Ghorbani

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# 1 Analysis of Plane Strain Foundation Using Orthotropic Elastic Material

## 1.1 Problem Description

This validation case demonstrates the use of orthotropic linear elasticity for a 2×2 m foundation model analyzed using Plane Strain Uncoupled (PLUnCoupled) mechanics. A uniform pressure of 100 kPa is applied over a central 0.1 m width. Due to the symmetric nature of the problem, only half of the domain is modeled to improve computational efficiency.

The example uses a **custom orthotropic UMAT** that allows specification of different elastic properties in three orthogonal directions, enabling more realistic modeling of naturally anisotropic materials such as: - Layered or stratified soils - Sedimentary deposits with preferential bedding planes - Geomaterials with inherent fabric anisotropy - Cross-anisotropic soils (transversely isotropic)

## 1.2 File Names

- **Static Implicit Solver** — Static analysis with orthotropic elasticity (isotropic-equivalent)
- **Anisotropic Variant** — Static analysis with moderately reduced vertical stiffness ( $E_2/E_1 \approx 0.7$ )
- **Strongly Anisotropic Variant** — Static analysis with **strongly** reduced vertical stiffness ( $E_2/E_1 \approx 0.3$ )

### 1.2.1 Simulation Setup

- Total Analysis Time: 1.0 (pseudo-time units)
- Time Step Size: Fixed increments (100 steps)
- Analysis Type: Static implicit

The purpose of this example is to demonstrate: 1. How to use the orthotropic elasticity UMAT in FALCON 2. The effect of material anisotropy on stress distributions 3. Comparison with isotropic elasticity to highlight directional stiffness effects

### 1.2.2 Model Geometry

The geometry is identical to the [isotropic elasticity validation](#):

*Figure 1: 2×2 m rectangular domain with a uniform pressure applied over a 0.1 m width.*

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## 1.3 FEM Model Setup

- **Analysis Type:** PLNonCoupled (Plane Strain Non-Coupled Mechanics)
- **Element Type:** N6P6 (6-node elements with 6 integration points)

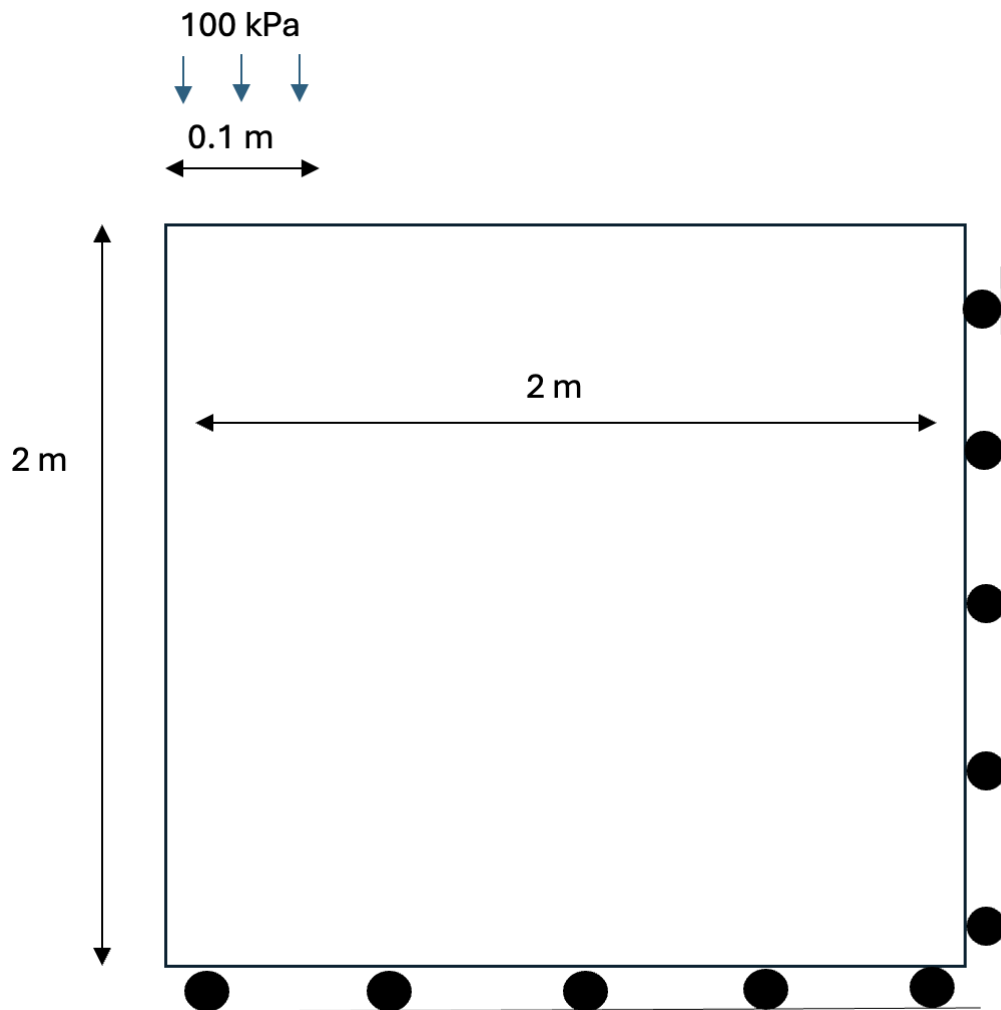


Figure 1: Figure 1: Geometry of the footing.

### 1.3.1 Geometry and Boundary Conditions

- **Domain Size:** 2 m × 2 m
- **Boundary Conditions:**
  - Lateral Boundaries: Restrained against horizontal movement  $u_x = 0$
  - Bottom Boundary: Restrained against vertical movement  $u_y = 0$
  - Symmetry Condition: Applied along  $x = 0$
  - Uniform Pressure: 100 kPa over a 0.1 m width on the top surface

## 1.4 Material Properties

The foundation soil is modeled as an orthotropic linear elastic material. In this **verification example**, the orthotropic parameters are chosen so that the UMAT reproduces the same response as the isotropic linear elastic model used in [ElasticityandBoussinesqsolution.md](#). That is, the orthotropic model is made *isotropically equivalent* to the baseline case.

### 1.4.1 Orthotropic Elastic Parameters (Isotropic-Equivalent)

**Young's Moduli:** -  $E_1$ : 210,000 kPa (x-direction) -  $E_2$ : 210,000 kPa (y-direction) -  $E_3$ : 210,000 kPa (z-direction)

**Poisson's Ratios (major):** -  $\nu_{12}$ : 0.30 -  $\nu_{23}$ : 0.30 -  $\nu_{31}$ : 0.30

**Shear Moduli (from  $E = 210,000$  kPa,  $\nu = 0.3$ ):** -  $G_{12}$ : 80,769.23 kPa -  $G_{23}$ : 80,769.23 kPa -  $G_{31}$ : 80,769.23 kPa

These values satisfy the isotropic relationship  $G = E/(2(1 + \nu))$  and ensure that the stiffness tensor of the orthotropic UMAT matches the isotropic linear elastic stiffness.

### 1.4.2 Mechanical Model Configuration

The orthotropic UMAT requires specification of all nine elastic constants. In the input file, it is defined using the tested @UMAT: syntax:

```
% Materials
Mat1
@UMAT: /Users/javadghorbani/Desktop/UMATLIB_FALCON/umat_for_falcon/
orthoelastic/OrthoEla/OrthoEla/OrthotropicUMAT.cpp
/Users/javadghorbani/Desktop/UMATLIB_FALCON/umat_for_falcon/orthoelastic/
OrthoEla/OrthoEla/OrthotropicUMAT.hpp Mechanical E1 210000 E2 210000 E3
210000 Nu12 0.30 Nu23 0.30 Nu31 0.30 G12 80769.23 G23 80769.23 G31 80769.23
@PhaseChar: Solid rhos 2.7
%%%
```

**Key Features:** - When  $E_1 = E_2 = E_3$ ,  $\nu_{12} = \nu_{23} = \nu_{31}$  and  $G_{12} = G_{23} = G_{31} = E/(2(1 + \nu))$ , the orthotropic model reduces exactly to the isotropic case. - The compliance matrix is

constructed and inverted to obtain the stiffness tensor. - All nine parameters must be specified; the model does not default to isotropic behavior unless the parameters are chosen as above.

### 1.4.3 Cross-Anisotropic Variants

Once the isotropic-equivalent behavior has been verified, anisotropy can be introduced by, for example: - Reducing  $E_2$  relative to  $E_1$  and  $E_3$  to represent softer vertical stiffness. - Modifying  $G_{23}$  independently to reflect different shear behavior in the vertical plane.

Such configurations are representative of many sedimentary soils where deposition creates preferential orientation of particles.

---

## 1.5 Step Definition

This analysis uses a static implicit solver with pseudo-time increments:

```
% Step Definitions
@@Step 1:
@@StartStep:      0
@@StepTime:      1.0      # Total pseudo-time units
@@NumberSteps:   100      # Fixed pseudo-time increments
@@SolverType:    Direct
@@SimMode:       Static   # Enforces static condition
@@OutputInterval: 10
@@OutputTypes:   Displacement TotalStress
@@ErrorTarget:   1.e-3
@@UL:           No
%%%
```

### 1.5.1 Step Configuration Details

- **@@SimMode: Static** → Specifies static analysis (no inertial or damping effects)
  - **@@StepTime: 1.0** → Pseudo-time serves as a load factor (not real time)
  - **@@NumberSteps: 100** → Divides the loading into 100 increments
  - **@@OutputInterval: 10** → Writes results every 10 steps
- 

## 1.6 Applied Loading

A uniform pressure of 100 kPa is applied over a 0.1 m width at the top surface:

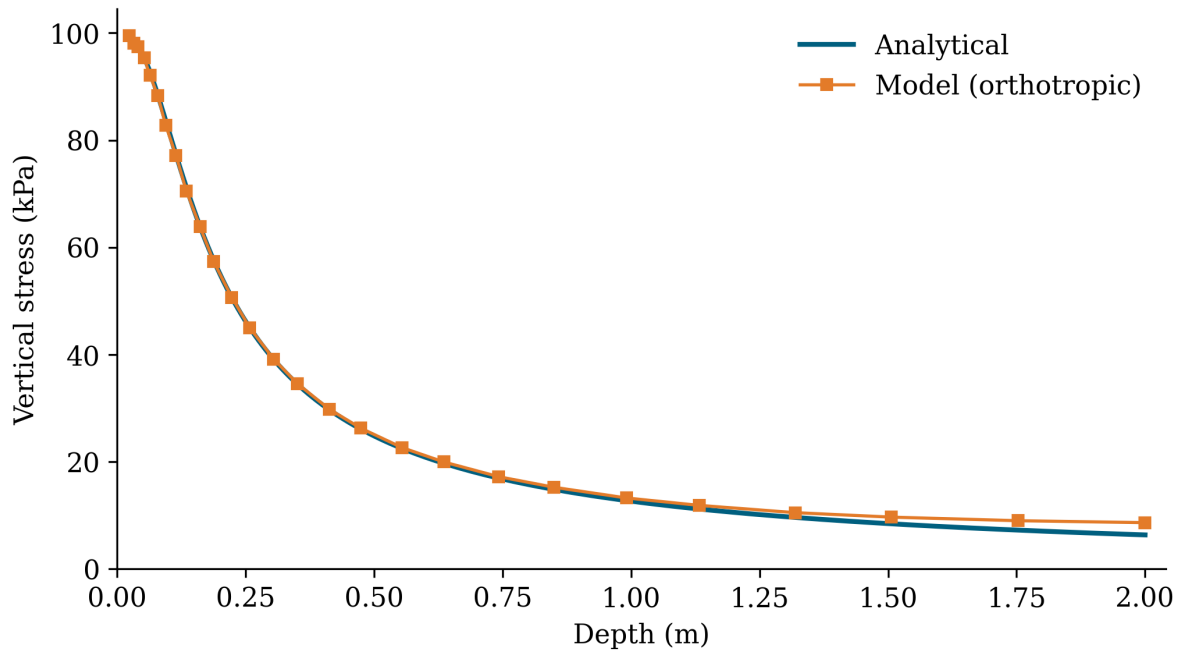


Figure 2: Vertical stress comparison vs. Boussinesq

```

% Stress Boundary
@StressBoundary 1
@@FaceID: Top
@@LoadType: Ramp
@@StressType: Normal
@@Amplitude: 100.0
@@StartStep: 1
@@ElementIDs: [elements beneath loaded area]
%%%

```

## 1.7 Results

### 1.7.1 Vertical Stress Distribution

The figure below compares the vertical stress  $\sigma_{yy}$  distribution along the centerline ( $x = 0$ ) for three cases: 1. **Isotropic elasticity** ( $E = 210,000$  kPa,  $\nu = 0.3$ ) – from [ElasticityandBoussinesqs-solution.md](#) 2. **Orthotropic elasticity** (as specified above) 3. **Boussinesq analytical solution** (isotropic reference)

Figure 2. Vertical stress  $\sigma_{yy}$  distribution beneath the center of the footing: comparison of isotropic and orthotropic elasticity against the Boussinesq analytical solution.

The orthotropic run that mimics the linear elastic case yields the following  $\sigma_{yy}$  values along the vertical line beneath the footing center (depth in meters, stress in kPa). When plotted against the Boussinesq analytical solution, these points lie essentially on the same curve, confirming that the orthotropic implementation reproduces the isotropic Boussinesq benchmark:

Depth (m)	Sigma_yy (kPa)
0.023211956	99.47706604
0.031939983	98.11301422
0.040668011	97.40164948
0.052199006	95.35447693
0.063730001	92.07455444
0.078964949	88.27919006
0.094200015	82.79805756
0.114328027	77.13669586
0.134456038	70.55395508
0.161049008	63.84557343
0.187643051	57.33114243
0.222777963	50.67352676
0.257912993	44.98585892
0.304332972	39.15298843
0.350754023	34.55972290
0.412083983	29.83571625
0.473413944	26.28702545
0.554443955	22.63064957
0.635473013	19.95921516
0.742529035	17.20999146
0.849583983	15.24631786
0.991026044	13.24357796
1.132467031	11.86501884
1.319339037	10.50565529
1.506211042	9.67252159
1.753105998	9.00380421
2.000000000	8.64286423

## 1.7.2 Effect of Anisotropy

*Figure 3. Depthwise stress comparison beneath the footing center for isotropic-equivalent (blue), moderately anisotropic (orange) and strongly anisotropic (green) runs.*

For the same applied pressure, the maximum settlement beneath the footing increases from approximately  $1.9 \times 10^{-4}$  m (isotropic-equivalent) to about  $2.3 \times 10^{-4}$  m (moderate anisotropy) and  $3.6 \times 10^{-4}$  m (strong anisotropy). Near the footing, stronger anisotropy gives higher horizontal stress and lower vertical stress, as more of the load is carried laterally in the stiff directions while the softer vertical direction deforms more.

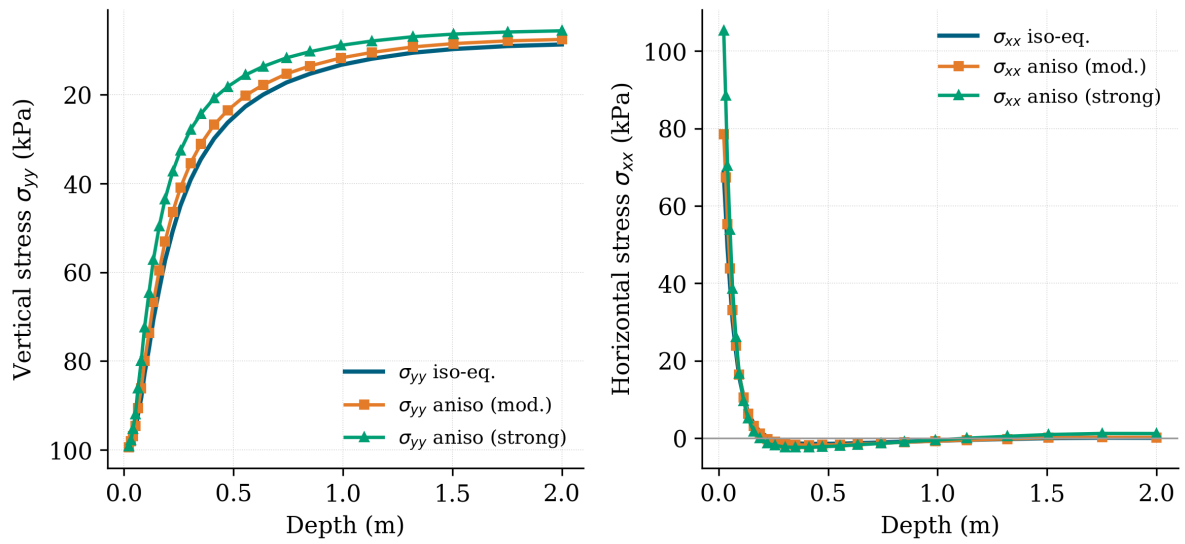


Figure 3: Comparison of isotropic-equivalent and anisotropic orthotropic stresses