



AD FALCON API Manual

Materials

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1 Materials

The `% Materials` section defines one or more materials and the properties assigned to each material. Elements reference materials by ID (the last token on each element line), so material IDs must match exactly.

For general rules about comments, numeric formats, and the `$name` tagging feature, see [Input File Structure](#).

1.1 Section header

FALCON treats section names as case-insensitive and whitespace-insensitive, so these headers are equivalent:

```
% Materials
%Materials
% materials
% MATERIALS
% Material_S
% Material-s
```

1.2 Syntax

```
% Materials
<MaterialID>
@<PropertyType>[:]? <PropertyDetails...>
@<PropertyType>[:]? <PropertyDetails...>
...
<MaterialID>
@<PropertyType>[:]? <PropertyDetails...>
...
%%%
```

1.3 Rules and behavior

- **Material ID line:**

- Any non-empty line that does **not** start with `@` starts a new material definition.
- Material IDs are case-sensitive (e.g., `Clay` and `cLay` are different).

- **Property (directive) lines:**

- Property lines must start with `@` (one or more leading `@` characters are accepted: `@ Perm`, `@@Perm`, `@@@Perm` behave the same).
- The directive name is case-insensitive (e.g., `@perm`, `@PERM`, `@Perm` are equivalent).

- A colon after the directive name is optional, and spacing after `:` is flexible:

```
* @Perm: Constant ...
* @Perm:Constant ...
* @Perm Constant ...
```

- **Comments:** `#` starts a comment anywhere on the line (inline comments are allowed).

1.4 Multiple materials and properties

- Define multiple materials by repeating the pattern `<MaterialID>` followed by one-or-more `@Property...` lines.
- All `@Property...` lines apply to the **most recent** material ID line.
- If the same material ID appears more than once in the section, its properties are accumulated under the same ID; avoid duplicates (for example, do not provide two `@UMAT:` lines for the same material unless you explicitly intend multiple entries).

1.5 Common directives

Directive names are case-insensitive (use the listed forms for readability):

- `@UMAT:` user-defined material (see [UMAT Development](#))
- `@Perm:` permeability (see [Permeability](#))
- `@PhaseChar:` phase properties (Solid, Liquid, Gas)
- `@SWRC:` soil-water retention curve (see [van Genuchten SWRC](#))
- `@EffectiveStress:` effective stress model (see [Ghorbani and Kodikara](#))
- `@AnisotropicPerm:` anisotropic permeability tensor coefficients

1.6 Minimum required content (by analysis type)

FALCON checks for a minimum set of required properties.

- **All analysis types:** a mechanical model is required (`@UMAT:` category Mechanical).
- **Coupled analyses (*Coupled):** also require liquid phase properties and permeability (`@PhaseChar: Liquid ...` and `@Perm: ...`). Anisotropic permeability (`@AnisotropicPerm:`) is optional; if omitted, isotropic behavior is assumed.
- **Fully coupled analyses (*FullyCoupled):** also require gas phase properties, an SWRC model, and an effective stress model (`@PhaseChar: Gas ...`, `@SWRC: ...`, `@EffectiveStress: ...`). In typical unsaturated models you will also provide `@PhaseChar: Liquid ...` and `@Perm: ...`. Anisotropic permeability (`@AnisotropicPerm:`) is optional; if omitted, isotropic behavior is assumed.

1.7 Tagging numeric values (optional)

You can tag any numeric value by inserting a `$name` token immediately before it. Tags do not change the analysis values; they are metadata used for parametric studies and surrogate

training (see [Parametric Studies](#)).

Examples (all equivalent for analysis):

```
% Materials
Clay
@UMAT:/path/to/LinearElasticUMAT.cpp /path/to/LinearElasticUMAT.hpp
Mechanical YoungsModulus=2.0e8 PoissonsRatio=0.3
@Perm: Constant k_sat $ksat 1e-7
@PhaseChar: Solid rhos 2.7
@PhaseChar: Liquid rhow $rho_w 0.997 K_l 2.25e6 l_viscosity 1.0e-6
%%%
```

1.8 Example Inputs

1.8.1 Example 1: User-Defined UMAT with Void Ratio Affected Permeability

```
% Materials
Mat2
@UMAT:/path/to/LinearElasticUMAT.cpp /path/to/LinearElasticUMAT.hpp
Mechanical YoungsModulus=2937600.0 PoissonsRatio=0.02
CustomVariable=dummy1,dummy2
@Perm: VoidRatioAffectedConstant k_sat 2.5e-12 e_ref 0.5
@PhaseChar: Solid rhos 2.7
@PhaseChar: Liquid rhow 0.997 K_l 2.25e6 l_viscosity 1.0e-6
@AnisotropicPerm: 1 1 1 0 0 0
%%%
```

- **Material ID:** Mat2
- **UMAT Properties:**
 - Source Files:
 - * .cpp: Path to user-defined material implementation.
 - * .hpp: Path to the corresponding header file.
 - Parameters:
 - * Young's Modulus: $E = 2,937,600$
 - * Poisson's Ratio: $\nu = 0.02$
 - * Custom Variables: dummy1, dummy2
 - See [UMAT Development](#) for details on implementing user-defined materials
- **Permeability:**
 - **Model:** [VoidRatioAffectedConstant](#)
 - **Parameters:**

- * Saturated Permeability: $k_{sat} = 2.5 \times 10^{-12}$
- * Reference Void Ratio: $e_{ref} = 0.5$

- **Phase Characterization:**

- Solid Density: $\rho_s = 2.7 \text{ g/cm}^3$
- Liquid:
 - * $\rho_w = 0.997 \text{ g/cm}^3$
 - * $K_l = 2.25 \times 10^6 \text{ Pa}$
 - * $\mu_l = 1.0 \times 10^{-6} \text{ Pa} \cdot \text{s}$

- **Anisotropic Permeability:**

- Diagonal terms: $k_{xx} = k_{yy} = k_{zz} = 1$
- Off-diagonal terms: $k_{xy} = k_{xz} = k_{yz} = 0$

1.8.2 Example 2: SWRC and Effective Stress Models

```
% Materials
Mat3
@SWRC: NonHysteretic alpha_1 0.0102 n 0.28 m 0.98 omega_prime 10.6 SW_max 1
SW_min 0
@EffectiveStress: GhorbaniKodikara Beta1 1.0 Beta2 0.0
@Perm: VanGenuchten m 0.98 k_sat 1.0e-10
@PhaseChar: Solid rhos 2.7
@PhaseChar: Liquid rhow 0.997 K_l 2.25e6 l_viscosity 1.0e-6
@PhaseChar: Gas rhog 1.1e-3 k_g 1.01e2 g_viscosity 1.8e-8
%%%
```

- **Material ID:** Mat3
- **Soil Water Retention Curve (SWRC):**
 - **Model:** [NonHysteretic van Genuchten](#)
 - **Parameters:**
 - * $\alpha_1 = 0.0102, n = 0.28, m = 0.98, \Omega' = 10.6$
 - * Saturation limits: $S_{w,max} = 1, S_{w,min} = 0$
- **Effective Stress:**
 - **Model:** [Ghorbani-Kodikara](#)
 - **Parameters:**
 - * $\beta_1 = 1.0, \beta_2 = 0.0$
- **Permeability:**

- **Model:** [Van Genuchten](#)

- **Parameters:**

- * $m = 0.98$, $k_{sat} = 1.0 \times 10^{-10}$

- **Phase Characterization:**

- Solid Density: $\rho_s = 2.7 \text{ g/cm}^3$

- Liquid:

- * $\rho_w = 0.997 \text{ g/cm}^3$

- * $K_l = 2.25 \times 10^6 \text{ Pa}$

- * $\mu_l = 1.0 \times 10^{-6} \text{ Pa} \cdot \text{s}$

- Gas:

- * $\rho_g = 1.1 \times 10^{-3} \text{ g/cm}^3$

- * $K_g = 1.01 \times 10^2 \text{ Pa}$

- * $\mu_g = 1.8 \times 10^{-8} \text{ Pa} \cdot \text{s}$



1.9 Supported Models and Parameters

1.9.1 SWRC Models (@SWRC)

Model	Required Parameters	Optional Parameters	Notes
Hysteretic	alpha_1, n, m, omega_prime, alpha_2, bd, bw, SW_max, SW_min, b_s_c	—	All 10 parameters required
Non Hysteretic	alpha_1, n, m, omega_prime	SW_max (default: 1.0)	

SW_min (default: 0.0) st (default: 1.0e15) | See [van Genuchten model](#) | | **BrooksAndCorey** | psi_b, lambda, SW_max, SW_min, omega_prime | — | All parameters required | | **FredlundXing** | Pb, nx, mx, omega_prime, SW_max, SW_min | — | All parameters required |

1.9.2 Effective Stress Models (@EffectiveStress)

Model	Parameters	Notes
GhorbaniKodikara	Beta1	

Model	Parameters	Notes
Beta2	Both parameters required; see GK2024 model	

1.9.3 Permeability Models (@Perm)

Model	Required Parameters	Optional Parameters	Notes
Constant	k_sat	—	Constant saturated permeability
VoidRatio Affected Constant	k_sat	e_ref (default: 0.0)	Void ratio affects permeability
Van Genuchten	m k_sat	e_ref (default: 0.0)	Van Genuchten relative permeability
BrooksCorey	lambda k_sat	e_ref (default: 0.0)	Brooks-Corey relative permeability
Van Genuchten Ke	m k_sat	ke_ref or e_ref (default: 0.0)	
k_min (default: 0.1)	Uses a separate void-ratio multiplier $k_e(e)$ together with $k_r(S_e)$ (see k_e multiplier)		
BrooksCorey Ke	lambda k_sat	ke_ref or e_ref (default: 0.0)	
k_min (default: 0.1)	Uses a separate void-ratio multiplier $k_e(e)$ together with $k_r(S_e)$ (see k_e multiplier)		

See [Permeability Models](#) for detailed formulations.

1.9.4 Phase Characteristics (@PhaseChar)

Phase	Parameters	Notes
Solid	rhos	Solid phase density (kg/m ³)
Liquid	rhow	

μ_l viscosity k_l | All three required | | **Gas** | ρ_{og} μ_g k_g | All three required |

1.9.5 Anisotropic Permeability (@AnisotropicPerm)

Format: @AnisotropicPerm: <XX> <YY> <ZZ> <XY> <ZX> <ZY>

Six permeability coefficients representing the full permeability tensor.

Optional: Anisotropic permeability is optional. When not specified, the code defaults to isotropic permeability behavior using the values from the @Perm: directive. When specified, the anisotropic permeability tensor components multiply the relative permeability calculated from the @Perm: model to create a full anisotropic permeability tensor.

1.9.6 User-Defined Materials (@UMAT)

Format: @UMAT: <cpp_path> <header_path> <category> [param1=value1 param2=value2 ...] [CustomVariable=var1,var2,...]

Categories: - Mechanical - Mechanical constitutive model - SWRC - Soil-water retention curve model - EffectiveStress - Effective stress model - Permeability - Permeability model - MohrCoulomb - Mohr-Coulomb constitutive model - Phase - Phase properties - AnisotropicPerm - Anisotropic permeability model

Parameters: - Parameters passed as name=value pairs - CustomVariable specifies internal state variable names (comma-separated, no spaces) - See [UMAT Development](#) for implementation details

1.10 Errors and validations

This section lists common error codes you may see while defining % Materials and how to resolve them. For a broader list of errors, see [Error Dictionary](#).

1.11 SWRC Model Errors (MF-o2XX)

Error Code	Message	Cause	Solution
MF-0201	Failed to parse all required properties for Hysteretic SWRC	Missing one or more required parameters	Provide all 10 parameters: alpha_1, n, m, omega_prime, alpha_2, bd, bw, SW_max, SW_min, b_s_c
MF-0202	Failed to parse all required properties for NonHysteretic SWRC	Missing required parameters	Provide required: alpha_1, n, m, omega_prime; optional: SW_max, SW_min, st
MF-0203	Failed to parse all required properties for Brooks and Corey SWRC	Missing required parameters	Provide all: psi_b, lambda, SW_max, SW_min, omega_prime
MF-0204	Failed to parse all required properties for FredlundXing SWRC	Missing required parameters	Provide all: Pb, nx, mx, omega_prime, SW_max, SW_min
MF-0205	Unknown SWRC model type	Unrecognized model name	Use: Hysteretic, NonHysteretic, BrooksAndCorey, or FredlundXing

1.12 Effective Stress Model Errors (MF-03XX)

Error Code	Message	Cause	Solution
MF-0301	Failed to parse Beta1 for Ghorbani & Kodikara	Missing or non-numeric Beta1	Provide Beta1 <numeric_value>
MF-0302	Failed to parse Beta2 for Ghorbani & Kodikara	Missing or non-numeric Beta2	Provide Beta2 <numeric_value>
MF-0303	Incomplete parameters for Ghorbani & Kodikara	Missing required parameters	Both Beta1 and Beta2 are required
MF-0304	Unknown Effective Stress model type	Unrecognized model name	Use: Ghorbani Kodikara

1.13 Permeability Model Errors (MF-04XX)

Error Code	Message	Cause	Solution
MF-0401	Failed to parse K_sat for Constant Permeability	Missing or non-numeric k_sat	Provide k_sat <numeric_value>
MF-0402	Failed to parse K_sat for VoidRatio AffectedConstant	Missing or non-numeric k_sat	Provide k_sat <numeric_value>, optionally e_ref <value>
MF-0403	Failed to parse m for Van Genuchten Permeability	Missing or non-numeric m	Provide m <numeric_value>
MF-0404	Failed to parse K_sat for Van Genuchten Permeability	Missing or non-numeric k_sat	Provide k_sat <numeric_value>
MF-0405	Failed to parse lambda for Brooks-Corey Permeability	Missing or non-numeric lambda	Provide lambda <numeric_value>
MF-0406	Failed to parse K_sat for Brooks-Corey Permeability	Missing or non-numeric k_sat	Provide k_sat <numeric_value>
MF-0407	Invalid permeability model type	Unrecognized model name	Use: Constant, Void RatioAffected Constant, Van Genuchten, or BrooksCorey

Note: e_ref is optional for void-ratio-affected models (defaults to 0.0 if not provided).

1.14 Phase Characterization Errors (MF-05XX)

Error Code	Message	Cause	Solution
MF-0501	Solid density not specified correctly	Missing rhos parameter	Provide rhos <density>
MF-0502	Liquid properties not specified correctly	Missing one or more liquid parameters	Provide all three: rhow <density> l_viscosity <viscosity> K_l <bulk_modulus>
MF-0503	Gas properties not specified correctly	Missing one or more gas parameters	Provide all three: rhog <density> g_viscosity <viscosity> k_g <bulk_modulus>
MF-0504	Invalid phase type	Unrecognized phase name	Use: Solid, Liquid, or Gas

1.15 Anisotropic Permeability Errors (MF-06XX)

Error Code	Message	Cause	Solution
MF-0601	Failed to parse anisotropic permeability coefficient	Missing or non-numeric value	Provide exactly 6 values: XX YY ZZ XY ZX ZY

1.16 UMAT Errors (MF-07XX)

Error Code	Message	Cause	Solution
MF-0701	UMAT cpp file does not exist at path	Invalid C++ source file path	Verify and correct the .cpp file path
MF-0702	UMAT header file does not exist at path	Invalid header file path	Verify and correct the .hpp or .h file path

UMAT Format: @UMAT: <cpp_path> <header_path> <category> [param1=value1 .. .] [CustomVariable=var1,var2,...]

Valid Categories: Mechanical, SWRC, EffectiveStress, Permeability, MohrCoulomb, Phase, AnisotropicPerm

1.17 Input Reader Verification Errors (IR-06XX)

These errors are raised during material verification after all materials are parsed:

Error Code	Message	Cause	Solution
IR-0601	UMAT property cannot coexist with standard property of same category	Both UMAT and built-in model defined for same category	Remove duplicate: use either UMAT or built-in model
IR-0602	Material missing required property (not covered by UMAT)	Required property for analysis type is missing	Add missing @ Property line or @ UMAT covering that category
IR-0603	Undefined material IDs found in elements	Elements reference undefined materials	Define all materials referenced in % Elements section

Material Requirements by Analysis Type: - **NonCoupled:** Requires UMAT Mechanical - **Coupled:** Requires UMAT Mechanical, Liquid, Perm - **FullyCoupled:** Requires UMAT Mechanical, SWRC, EffectiveStress, Liquid, Gas, Perm
