

Consistent Engineering Units In Finite Element Analysis

New to FEA and don't want to read the full document? Here's the very short summary if you need to work with a "units-free" FEA system. A units conversion table starts on page 4.

- What length units are you using? If you have imported geometry from elsewhere, then measure some distances to figure out what length units were used.
- Choose your preferred unit of force.
- Derive ALL other physical units from your chosen Force and Length units (assumes you will be using seconds as the standard unit of time!).
- For example, Length = mm, Force = N, then Pressure = Stress = Youngs Mod = $\text{N/mm}^2 = \text{MPa}$. $F=ma$, thus mass MUST be Tonnes because acceleration = mm/sec^2 . Thus density MUST be Tonnes/ mm^3 , eg. 7.8×10^{-9} for a typical steel.
- Similarly, if Length = inch, Force = pounds, then Pressure = Stress = Youngs Mod = $\text{lbs/in}^2 = \text{psi}$. $F=ma$, thus mass MUST be slug-inch (this mass weighs ~386lbf on earth). Thus density MUST be slug-inch/ in^3 , eg. 7.3×10^{-4} for a typical steel.

Depending on the modelling software you use for your Finite Element Analysis (FEA), your modelling process often requires an understanding of consistent engineering units.

Although some FEA modellers may provide a convenient method of declaring which unit you are applying at any instant, many FEA modellers and most FEA solvers are "units-free".

Therefore, it is critical to understand consistent units if you are:

- transferring a model or solver file to/from somewhere else;
- reviewing someone else's FEA work; or
- using any FEA modeller which leaves the units up to you.

When the units are left up to the user, "consistent units" must be used.

SI Units

The easiest set of consistent units is the SI system of metres (meters), kilograms and seconds.

These derive associated units that are commonly used by designers/engineers/analysts, such as Newtons, Joules, Watts, Pascals, and used to quantify measures such as density, acceleration, velocity, viscosity, specific heat and many more.

The important point about using consistent units is the necessity to stick with units that work correctly together - not to mix units that do not have a correct relationship with each other.

For example, if using the basic SI units of metres, kilograms and seconds, then:

- **Density** must be in kg/m^3 ;

- **Acceleration** must be in metres/sec²;
- **Force** must be in Newtons, because a Newton is the force it takes to accelerate 1kg at the rate of 1m/sec². (Force = mass x acceleration, ignoring relativity effects of course), and
- **Power** must be in Watts = (Newtons x metres) per second.

Some engineering companies instruct their engineers to use basic SI units so there are no questions about unit conversion or consistent units. However, this has its downsides, particularly when using FEA.

Many people find the use of metres inconvenient, and the use of millimetres by CAD designers is popular. And... there are some particular problems to be avoided when using metres with the very common Nastran "small field" format. With only 8 characters wide per field, a location at -1.0154mm will be written as -1.015-3 (metres) which is effectively only 4 significant figures. For models with fine details or where precise contact is involved, precision down to only 1/1000th mm may not be enough. In extreme cases, closely spaced nodes can be written out at the same coordinate location, which will typically produce NOGO fatal error messages due to element quality.

So, as an aside, if you are using metres and Nastran (or any other solver which uses text analysis files), we recommend you use large field (double precision) format if it is not the default in your modelling system. We also recommend using large field format if you are modelling small details which are "distant from the model origin" (regardless of units) for similar reasons of precision.

Anyway, back to units. If you make the popular choice of millimetres, and prefer using Newtons for force, then this has specific consequences in your use of all other units to preserve consistency:

- Applied **Pressures** are Newtons / mm², which is MegaPascals (MPa)
- **Stress results** are thus also MPa.
- **Young's Modulus** is also in units of pressure, and is thus also MPa.

What is less obvious is that in choosing millimetres and Newtons, you have also forced a change in your mass units. This is because $F=ma$, and so the question which needs to be answered is:

"What mass accelerates at 1mm/sec² when a force of 1N is applied?"

1mm/sec² is very slow (1000 times less than 1m/sec², of course) - the answer is 1 Tonne.

Therefore, density is in Tonnes per cubic mm – eg. 1e-9 for water and 7.8e-9 for a typical steel.

So, if you are running any gravity analysis (having chosen millimetres and Newtons), then 1g is 9810 (mm/sec²), point masses are Tonnes and density is in Tonnes / mm³. **Natural frequency analyses will be wrong if mass or density is inconsistent, despite no gravity loads being applied!**

Additional consequences of choosing millimetres and Newtons occur for heat transfer:

- **Conductivity** in standard SI: Watts per (metre x Kelvin)
 - Conductivity in your consistent units: milliWatts per (millimetre x Kelvin).
Therefore 1W/m.K = 1mW/mm.K

- **Heat Flux** in Standard SI: Watts per square metre
 - Heat Flux in your consistent units: milliWatts per square millimetre. Therefore numeric input would be reduced by a factor of 1000 compared to Standard SI. Eg. $13\text{W/m}^2 = 0.0013\text{mW/mm}^2$.
- The same conversion is required for a **convection coefficient** - ie. $\text{W/m}^2\cdot\text{K}$ becomes $\text{mW/mm}^2\cdot\text{K}$ so numeric input also reduces by a factor of 1000.
- **Specific Heat** in Standard SI: Joules per (kilogram x Kelvin)
 - Specific Heat in your consistent units: milliJoules per (Tonne x Kelvin). Therefore numeric input would be increased by a factor of $1\text{e}6$ compared to Standard SI. eg. $4180 [\text{J/kg}\cdot\text{K}]$ becomes $4.18\text{e}9 [\text{mJ/T}\cdot\text{K}]$

Note that results such as heat flux will obviously be presented in the same consistent units you have chosen to apply.

Imperial Units

For those who use Imperial Units, the same necessity to use a consistent set of units still applies. The relationships are less tidy, because these measures were invented before real science. If doing any *coupled mechanical / thermal / fluids analysis*, then it is best to avoid using Imperial Units, on the basis that material properties are rarely listed in a consistent units measure.

For engineering, a consistent set of Imperial Units is slug (mass), foot (length) and seconds (time).

It is critical to note that a pound is not a unit of mass *for engineers or scientists* and should never be used as a unit of mass. Science required the "invention" of a slug as a real mass unit in the Imperial system.

A pound is a unit of force in engineering.

1 pound is the unit of force which accelerates 1 slug at 1 foot/sec^2 . As most of us do not size each other up by estimating a person's "weight" in slugs, it is thus useful to know that a mass of one slug weighs about 32 pounds force on earth ($1g = 32.19 \text{ ft/sec}^2$ and $F = ma$).

Again, for many people, the use of feet for length is inconvenient, so inches are often used instead, which thus means some conversions are required to preserve a consistent set of units.

The obvious consequence of using inches is that applied pressures, stress results and Youngs Modulus are all in psi (pounds per square inch). This is common, as many sources supply material constants in these units.

Not so obvious, if using pounds force and inches, is that mass is now in units of "12 x slugs" = "slug-inch". Although some have named this mass unit the "slinch" or "blob", we prefer the colloquially applied name, the "snail". (Thanks to Dr Tim Coates of GKN Aerospace for supplying this useful name for the unit - we are unsure as to whether the term has earlier origins). Thus density must be in units of snails per cubic inch, which for a typical steel would be 7.3e^{-4} . A snail weighs about 386 pounds force on earth (it is a large snail).

If doing thermal analysis using Imperial Units (in inches), then consistent units would be:

- inch pounds for **Work**
- inch pounds per second for **Power**
- (inch pounds per second) per square inch for **Heat Flux**
- inch pounds per (snail x degree) for **Specific Heat**.

Most sources do not supply material constants / coeffs / equations in these units (even densities are often misquoted as weight densities), so substantial conversion and care is required.

Below is a table of some typical mechanical and thermal units with their equivalent values in four columns of commonly used consistent unit sets for FEA. Note that it is possible to use "hybrid" combinations of consistent units, where certain properties (eg. energy, power, temperature) may use different self-consistent units values compared to the remainder of the units set. This requires extreme caution if the physics is coupled and our conservative recommendation is never to use such an approach. On that basis, the table ignores the possibility of doing so.

Note that due to some minor variations in the definitions of some values (such as g, BTU and derived properties), other sources may show a difference of a few units variation in the 4th significant figure for some of the values in the table. For the approximations associated with FEA, such variations are insignificant.

	Each column represents a typical consistent unit set for FEA. The length units of your geometry dictate which single consistent column set to use.			
Property/value	SI, Standard: N,m,kg,s,°K	SI, mm: N,mm,T,s,°K	Imperial, inches: Lbf, in, snail,s,°F Snail = slug-inch =386.2 "lb mass"	Imperial, feet: Lbf,ft,slug,s,°F Slug = 32.19 "lb mass"
1 pound (Force)	4.449 Newton	4.449 N	1.000 lbf	1.000 lbf
1 Newton (Force)	1.000 N	1.000 N	0.2248 lbf	0.2248 lbf
1 kg (Mass)	1.000 kilogram	1.000e ⁻³ Tonne	5.709e ⁻³ snails	6.851e ⁻² slugs
1 slug (Mass)	14.60 kg	1.460e ⁻² T	8.333e ⁻² snails	1.000 slug
1 snail (Mass)	175.2 kg	0.1752 T	1.000 snail	12.00 slugs
1 "pound mass" lbm	0.4535 kg	4.535e ⁻⁴ T	2.589e ⁻³ snails	3.107e ⁻² slugs
1 metre (Length)	1.000 m	1000 mm	39.37 in	3.281 ft
1 inch (Length)	0.0254 m	25.4 mm	1.000 in	8.333e ⁻² ft
1 foot (Length)	0.3048 m	304.8 mm	12.00 in	1.000 ft
1 Pascal (Pressure)	1 N/m ²	1.000e ⁻⁶ MPa	1.450e ⁻⁴ psi	2.088e ⁻² lbf/ft ²
1 psi (Pressure)	6896 Pa	6.896e ⁻³ MPa	1.000 psi	144.0 lbf/ft ²
1 MPa (Pressure)	1.000e ⁶ Pa	1.000 MPa	145.0 psi	20885 lbf/ft ²
1 g (Acceleration)	9.810 m/sec ²	9810 mm/sec ²	386.2 in/sec ²	32.19 ft/sec ²
1 m/sec ² (Accel.)	1.000 m/sec ²	1000 mm/sec ²	39.37 in/sec ²	3.281 ft/sec ²
1 ft/sec ² (Acceleration)	0.3048 m/sec ²	304.8 mm/sec ²	12.00 in/sec ²	1.000 ft/sec ²
1kg/m ³ (Density)	1.000 kg/m ³	1.000e ⁻¹² T/mm ³	9.356e ⁻⁸ snails/in ³	1.940e ⁻³ slugs/ft ³
Continued next page				

1 lbm/ft ³ (Density)	16.02 kg/m ³	1.602e ⁻¹¹ T/mm ³	1.498e ⁻⁶ snails/in ³	3.107e ⁻² slugs/ft ³
1 lbm/in ³ (Density)	2.768e ⁴ kg/m ³	2.768e ⁻⁸ T/mm ³	2.589e ⁻³ snails/in ³	53.69 slugs/ft ³
1 Joule (Energy)	1.000 N.m ie. Joule	1000 N.mm ie. mJ	8.849 in.lbf	0.7374 ft.lbf
1 BTU (Energy)	1,055 Joules	1.055e ⁶ mJ	9334 in.lbf	777.8 ft.lbf
1 Calorie (Energy)	4.186 Joules	4186 mJ	37.04 in.lbf	3.086 ft.lbf
1 Watt (Power)	1.000 N.m/sec ie. Watt	1000 N.mm/sec ie. mW	8.849 in.lbf/sec	0.7374 ft.lbf/sec
1 BTU/hr (Power)	0.2930 Watts	293.0 mW	2.593 in.lbf/sec	0.2161 ft.lbf/sec
1 BTU/sec (Power)	1055 Watts	1.055e ⁶ mW	9334 in.lbf/sec	777.8 ft.lbf/sec
1 HP (Power)	745.8 Watts	7.458e ⁵ mW	6600 in.lbf/sec	550.0 ft.lbf/sec
1 Calorie/sec (Power)	4.186 Watts	4186 mW	37.04 in.lbf/sec	3.086 ft.lbf/sec
1 Watt/m ² (Heat Flux)	1.000 W/m ²	1.000e ⁻³ mW/mm ²	5.709e ⁻³ in.lbf/sec.in ²	6.851e ⁻² ft.lbf/sec.ft ²
1 BTU/hr/ft ² (Heat Flux)	3.155 W/m ²	3.155e ⁻³ mW/mm ²	1.801e ⁻² in.lbf/sec.in ²	0.2161 ft.lbf/sec.ft ²
1 HP/ft ² (Heat Flux)	8028 W/m ²	8.028 mW/mm ²	45.83 in.lbf/sec.in ²	550.0 ft.lbf/sec.ft ²
1 calorie/sec/in ² (Heat Flux)	6488 W/m ²	6.488 mW/mm ²	37.04 in.lbf/sec.in ²	444.5 ft.lbf/sec.ft ²
Temperature given in Kelvin (#K) Celsius (#C) Fahrenheit (#F)	K = #F x 5/9 + 255.37 K = #C x 1 + 273.15 C = #F x 5/9 - 17.778 C = #K x 1 - 273.15		F = #K x 1.8 - 459.67 F = #C x 1.8 + 32	
1 J/kg.K (Specific Heat)	1.000 N.m/kg.K	1.000e ⁶ N.mm/T.K	861.1 in.lbf/snail.°F	5.980 ft.lbf/slugg.°F
1 BTU/lbm.F (Specific Heat)	4186 J/kg.K	4.186e ⁹ mJ/T.K	3.605e ⁶ in.lbf/snail.°F	2.503e ⁴ ft.lbf/slugg.°F
1 kcal/lbm.F (Specific Heat)	1.662e ⁴ J/kg.K	1.662e ¹⁰ mJ/T.K	14.31e ⁶ in.lbf/snail.°F	9.936e ⁴ ft.lbf/slugg.°F
1 W/m.K (Conductivity)	1.000 W/m.K	1.000 mW/mm.K	0.1249 in.lbf/sec.in.°F	0.1249 ft.lbf/sec.ft.°F
1 BTU/hr.ft.°F (Conductivity)	1.730 W/m.K	1.730 mW/mm.K	0.2161 in.lbf/sec.in.°F	0.2161 ft.lbf/sec.ft.°F
1 W/m ² .K (Convection)	1.000 W/m ² .K	1.000e ⁻³ mW/mm ² .K	3.172e ⁻³ in.lbf/sec.in ² .°F	3.806e ⁻² ft.lbf/sec.ft ² .°F
1 BTU/hr.ft ² .°F (Convection)	5.678 W/m ² .K	5.678e ⁻³ mW/mm ² .K	1.801e ⁻² in.lbf/sec.in ² .°F	0.2161 ft.lbf/sec.ft ² .°F
1 kcal/hr.ft ² .°F (Convection)	22.53 W/m ² .K	2.253e ⁻² mW/mm ² .K	7.146e ⁻² in.lbf/sec.in ² .°F	0.8576 ft.lbf/sec.ft ² .°F

Our recommendations:

1. ALWAYS use consistent units. That means the base units of Mass, Length, Time, Temp must comply with any/all derived associated units you are using in your analysis (such as pressure, force, velocity, density, acceleration, convection etc.). Then you won't get caught out when your static gravity analysis works OK using mm, N, MPa, kg/mm^3 and m/sec^2 , but is instantly wrong as soon as you run a simple natural frequency analysis, or otherwise more advanced analyses.
2. Use metric if you can - the availability of material data and constants in workable imperial units (particularly in thermal and fluids analysis) typically requires arduous conversion to maintain a consistent set of units for analysis. However, units conversion of any sort is best minimised, so you do not become the person blamed for losing the next Mars Climate Orbiter!
3. PARAM, WTMASS is available in NASTRAN so analysts can use force units as masses (eg. non-structural mass in pounds per square foot). We believe this practice should be rigorously avoided (except by analysts of the highest expertise), and that proper consistent units are always used. It is much easier to convert imperial inputs to real mass units (such as slugs and slug-inches, rather than non-mass units such as pounds) than to test the full scope of all NASTRAN analysis types for which WTMASS correctly operates.

These guidelines have been assembled by and for Nastran users; however, the information is equally applicable to users of Femap, Ansys, Abaqus, MSC.Software, MSC Marc, Patran, Ideas, Strand, Algor, Cosmos, CosmosWorks and many others.

EnDuraSim has decades of hands on experience in FEA, particularly using Femap and Nastran. We provide [general training in FEA or specific training for Femap and NX Nastran](#). We provide [quality FEA consulting](#), typically fixed price contract for defined scope of work. We provide yearly unlimited (within reason) [technical support for Femap with NX Nastran](#). We provide Femap API programming products and services to enhance analyst productivity. [Contact us](#) for further information.