Consistent Engineering Units In Finite Element Analysis

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

Note that although your FEA user interface may provide a convenient method of declaring which unit you are applying at any instant, it is important to know that almost every FEA solver does not show units in the "input file".

Therefore, it is critical to understand units if you are:
• taking a model from somewhere else;
• reviewing someone else's FEA work, or simply
• using any FEA modeller which leaves the units up to you.

When the units are left up to the user, the important point to note is the necessity to use "consistent units".

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, plus generically titled items such as density, acceleration, velocity, viscosity 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/m3 ;
• 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.

Many 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 so the use of millimetres (millimeters) by CAD designers is very popular. Similarly, there are some particular problems to be avoided when using metres with the very popular Nastran "small field" format. With only 8 characters wide per field, a location at -1.015mm will be described as -1.02e-3 (metres) which is effectively only 3 significant figures. For models with fine details or where precise contact is involved, precision down to only 1/100 of a millimetre is not enough. In extreme cases, closely spaced nodes can be written out at the same coordinate location, which will typically produce fatal error messages.

So, as an aside, if you are using metres and Nastran, we recommend you use large field format if it is not the default in your modelling system. We also recommend using large field format if you are modelling fine details which are "distant from the model origin" 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.

The obvious consequences of choosing Newtons and millimetres are:

- 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 asked 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 - thus 1e-9 for water and 7.8e-9 for a typical steel.

So, if you are running an analysis where gravity is involved (having chosen millimetres and Newtons), then the magnitude of acceleration is 9810 (mm/sec2), point masses are Tonnes and density is in Tonnes / mm3 .

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 no change in the numeric value input)
- 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.
- The same conversion is required for a convection coefficient - ie. W/m2 K becomes mW/mm2 K so numeric input 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 1e6 compared to Standard SI. eg. 4180 [J/kgK] becomes 4.18e9 [mJ/TK]

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 of you who use Imperial Units, you have our sincerest condolences, however the same set of principles apply. A consistent set of units must be used in order to produce a valid analysis. For engineering, a basic 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 and should not be used as a unit of mass.

A pound is a unit of force

A pound is the unit of force required to accelerate a slug at "1g", which is 32.19 feet/sec2 . 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 (from the definition above).

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 is that mass is now in units of "12 x slugs". 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 could be applied by using:
- 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*

As most texts do not conveniently supply material constants or coefficients or equations using these units (even densities are often misquoted as weight densities), then some additional conversion and care is required.

Below is a table of some common 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 caution if the physics is coupled and our conservative recommendation is not 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.				
	SI, Standard: N,m,kg,s,^{0}K	**SI, mm: N,mm,T,s,^{0}K**	**Imperial, inches: Lbf, in, snail,s,^{0}F snail=slinch,blob =386.2 "lb mass"**	**Imperial, feet: Lbf,ft,slug,s,^{0}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 ft/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
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.	1000 N.mm	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.	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	$5.709e^{-3}$	$6.851e^{-2}$
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

	SI, Standard: N,m,kg,s,ºK	SI, mm: N,mm,T,s,ºK	Imperial, inches: Lbf, in, snail,s,ºF snail=slinch,blob =386.2 "lb mass"	Imperial, feet: Lbf,ft,slug,s,ºF Slug = 32.19 "lb mass"
1 HP/ft2 (Heat Flux)	8028 W/m2	8.028 mW/mm2	45.83 in.lbf/sec.in2	550.0 ft.lbf/sec.ft2
1 calorie/sec/in2 (Heat Flux)	6488 W/m2	6.488 mW/mm2	37.04 in.lbf/sec.in2	444.5 ft.lbf/sec.ft2
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	1.000e6 N.mm/T.K	861.1 in.lbf/snail.ºF	5.980 ft.lbf/slug.ºF
1 BTU/lbm.F (Specific Heat)	4186 J/kg.K	4.186e9 mJ/T.K	3.605e6 in.lbf/snail.ºF	2.503e4 ft.lbf/slug.ºF
1 kcal/lbm.F (Specific Heat)	1.662e4 J/kg.K	1.662e10 mJ/T.K	14.31e6 in.lbf/snail.ºF	9.936e4 ft.lbf/slug.ºF
1 W/m.K (Conductivity)	1.000 W/m.K	1.000 mW/mm.K	0.1249 in.lbf/sec.in.ºF	0.1249 ft.lbf/sec.ft.ºF
1 BTU/hr.ft.ºF (Conductivity)	1.730 W/m.K	1.730 mW/mm.K	0.2161 in.lbf/sec.in.ºF	0.2161 ft.lbf/sec.ft.ºF
1 W/m2.K (Convection)	1.000 W/m2.K	1.000e-3 mW/mm2.K	3.172e-3 in.lbf/sec.in2.ºF	3.806e-2 ft.lbf/sec.ft2.ºF
1 BTU/hr.ft2.ºF (Convection)	5.678 W/m2.K	5.678e-3 mW/mm2.K	1.801e-2 in.lbf/sec.in2.ºF	0.2161 ft.lbf/sec.ft2.ºF
1 kcal/hr.ft2.ºF (Convection)	22.53 W/m2.K	2.253e-2 mW/mm2.K	7.146e-2 in.lbf/sec.in2.ºF	0.8576 ft.lbf/sec.ft2.ºF

Our recommendations:

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.).

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!

PARAM, WTMASS is available in NASTRAN so analysts can use force units as masses (eg. nonstructural 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.

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.