FEAKalc 3D

Concrete Design Manual to AS3600-2018

Document Revision

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1. Introduction

1.1. Overview

FEAKalc 3D incorporates reinforced concrete member design directly within the structural analysis environment. The concrete design module uses the internal forces obtained from the three-dimensional finite element model to assess reinforced concrete beams and columns in accordance with the design procedures implemented for AS 3600.

The concrete design calculations are performed at member level using the actual analysis actions recovered from the FEAKalc 3D structural model. Frame elements may be treated either as beams or columns, allowing the appropriate design methodology to be applied according to the intended structural function of the member.

For concrete beams, FEAKalc 3D evaluates flexural reinforcement requirements and shear reinforcement requirements at discrete locations along the member. The flexural design determines the required tension reinforcement and, where necessary, compression reinforcement. The shear design determines the required transverse reinforcement expressed as

$$A_{sv}/s$$

For concrete columns, FEAKalc 3D evaluates combined axial compression and bending about both principal section axes. Uniaxial axial-force–moment interaction curves are generated independently for the two principal directions, after which a biaxial interaction assessment is performed using the calculated capacities corresponding to the applied axial load.

The concrete design module therefore acts as the link between the global finite element analysis and the local reinforced concrete section design.

1.2. Design Philosophy

The FEAKalc 3D concrete design methodology is based on the principle that design actions should be obtained directly from the structural model and assessed using section-level reinforced concrete calculations.

The analysis and design processes remain distinct. The finite element solver determines the structural response, including axial forces, bending moments, shear forces and torsional actions. These forces are subsequently passed to the concrete design module, where the appropriate beam or column design procedure is applied.

For beam design, the current implementation uses:

$$M^* = M_{33}$$

for flexure, together with:

$$V^* = V_2$$

for the corresponding shear design.

Axial compression from the finite element model is also passed into the beam flexural calculations. FEAKalc adopts the finite element sign convention in which compression is negative, and converts this internally to a positive compression force for the concrete section calculations:

$$N_c = \max(0, -N)$$

The beam design procedure evaluates the section at each supplied design station. For each station, the program determines the required tension steel A_{sT}, compression steel A_{sC}, design flexural capacity ϕM_u, and required shear reinforcement A_{sv}/s.

Column design is performed using a strain-compatibility approach. The strain distribution across the section is varied to generate axial-force–moment interaction curves about the two principal section directions. The concrete compression block and reinforcement forces are integrated through equilibrium to determine the available section capacity.

Member slenderness is incorporated using a moment-magnification procedure. The column design moments are therefore based on the governing applied end moments together with the calculated magnification associated with member effective length and axial load.

The final column assessment includes:

- weak-axis axial-force–moment interaction;
- strong-axis axial-force–moment interaction;
- moment magnification about each direction; and
- biaxial interaction between the two principal bending directions.

1.3. Scope of the Concrete Design Module

The present FEAKalc 3D concrete design module includes reinforced concrete beam and rectangular column design.

For beams, the design engine currently supports rectangular sections. Internally, the rectangular section is passed through the general T-beam flexural engine by taking the flange width equal to the web width. This allows the same strain-compatibility and force-equilibrium routines to be used while retaining rectangular section behaviour.

The beam design procedure includes:

- flexural design about the local 3-axis;
- tension reinforcement;
- compression reinforcement where required;
- minimum flexural reinforcement;
- flexural strength reduction;
- section capacity;
- shear design associated with local V_2;
- concrete shear contribution;
- minimum shear reinforcement;
- required A_{sv}/s; and
- maximum shear stress assessment.

For columns, the present implementation includes rectangular reinforced concrete sections with reinforcement distributed around the section perimeter.

The column design procedure includes:

- axial compression;
- bending about both principal axes;
- concrete stress-block parameters dependent on f_c';
- reinforcing steel strain and stress;
- generation of axial-force–moment interaction curves;

- pure compression and pure bending regions;
- moment magnification;
- minimum eccentricity;
- weak- and strong-axis utilisation;
- biaxial interaction; and
- automatic reinforcement optimisation for rectangular sections.

Circular column optimisation is identified in the present implementation but is not yet completed. Accordingly, circular column design should not presently be described as part of the supported FEAKalc 3D concrete design scope.

1.4. Relationship to the Finite Element Analysis

FEAKalc 3D does not generate independent simplified design moments for concrete members. The concrete module receives the actions calculated by the global structural analysis.

Each concrete beam design station may contain:

$$N, \quad M_{22}, \quad M_{33}, \quad V_2, \quad V_3, \quad T$$

together with its position along the member.

For the currently implemented beam design direction, FEAKalc extracts M_{33} and V_2. The moment sign is retained so that positive and negative bending may be represented correctly when reinforcement results are subsequently displayed along the member.

For columns, the analysis moments at the member ends are used together with the axial load and effective member length to establish the design moments about the two principal axes.

This approach allows the reinforcement demand shown within FEAKalc 3D to correspond directly to the force diagrams produced by the same structural model.

1.5. Overall Concrete Design Workflow

The overall concrete design procedure may be summarised as:

- Finite element model
- structural analysis →
- recovery of frame actions →
- member classification as beam or column →
- section-level concrete design →
- reinforcement and utilisation results →
- graphical design display and calculation memo.
- For a beam:
    - Recover M_{33}, V_2 and N
    - flexural section analysis
    - determine A_{sT} and A_{sC}
    - calculate ϕM_u
    - shear assessment
    - determine A_{sv}/s
    - report governing reinforcement.
- For a column:
    - Recover N, end moments and effective lengths
    - establish minimum eccentricity
    - calculate moment magnification
    - generate weak-axis interaction curve

- generate strong-axis interaction curve
- determine capacities at the applied axial force
- perform biaxial interaction check
- report utilisation.

2. Reinforced Concrete Beam Design

2.1. Flexural Design Methodology

2.1.1. General

Following completion of the structural analysis, FEAKalc 3D performs reinforced concrete beam design using the actions calculated at the design stations along each frame element.

For the current concrete beam implementation, flexural design is carried out about the member local 3-axis using the analysis moment:

$$M^* = M_{33}$$

The corresponding local shear action is V_2. Axial force is also transferred to the concrete design routine, with negative finite-element axial force interpreted as compression:

$$N_c = \max(0, -N)$$

The design is carried out independently at each station. This allows the required longitudinal reinforcement to vary along the beam in accordance with the calculated bending-moment distribution.

2.1.2. Section Geometry

The current FEAKalc 3D beam implementation designs **rectangular reinforced concrete sections**.

The underlying flexural calculation routine is capable of treating a flanged section. For FEAKalc 3D rectangular beams, this general routine is called with the flange width equal to the beam width. The resulting behaviour is therefore that of a rectangular section while retaining the common section-analysis engine.

The principal geometric quantities used in the calculation are:

$b =$ beam width $D =$ overall beam depth $c =$ reinforcement cover

and the effective depth is taken as:

$$d = D - c$$

A separate compression reinforcement depth d' is also available to the calculation. Where a valid compression cover has not been supplied, FEAKalc substitutes the normal beam cover.

2.1.3. Concrete Stress Block

The concrete compression zone is represented using an equivalent rectangular stress block.

The stress-block parameters are calculated directly from the specified concrete compressive strength f_c':

$$\alpha_2 = \max(0.67,\ 0.85 - 0.0015 f_c')$$

and:

$$\gamma = \max(0.67,\ 0.97 - 0.0025 f_c')$$

where f_c' is expressed in MPa.

For a neutral-axis depth c_n, the equivalent stress-block depth is:

$$a = \gamma c_n$$

The concrete compression force is then determined from the stress-block geometry and the stress:

$$\alpha_2 f_c'$$

For the rectangular FEAKalc beam section, the compression force therefore follows the rectangular section geometry associated with the specified beam width.

2.1.4. Strain Compatibility

The section calculation uses strain compatibility to establish the stresses developed in the longitudinal reinforcement.

The maximum concrete compressive strain adopted by the calculation is:

$$\varepsilon_{cu} = 0.003$$

and the reinforcing steel modulus is:

$$E_s = 200\,000 \text{ MPa}$$

For reinforcement at a depth y_s, the steel strain is obtained from the linear strain distribution through the section. The corresponding elastic steel stress is calculated from:

$$f_s = E_s \varepsilon_s$$

with the calculated stress limited to the specified reinforcing steel yield strength f_y.

Accordingly, the reinforcement is not automatically assumed to be at yield. Its stress depends upon the calculated neutral-axis position and the resulting strain at the reinforcement level.

2.1.5. Section Equilibrium

For a trial neutral-axis position, FEAKalc establishes equilibrium between the concrete compression force, tension reinforcement, compression reinforcement and applied axial compression.

The implemented equilibrium calculation may be expressed conceptually as:

$$C_c + C_s + T_s - P_t - N_c = 0$$

where:

C_c is the concrete compression-block force,

C_s is the force developed in compression reinforcement,

T_s is the force developed in the nominal tension reinforcement,

P_t represents prestressing force where applicable to the underlying general beam routine, and

N_c is the applied axial compression.

For FEAKalc 3D reinforced concrete beam design, the prestressing inputs are passed as zero.

The neutral axis is therefore established from force equilibrium rather than by assuming that both layers of reinforcement have yielded.

2.1.6. Direction of Bending

The magnitude of the design moment is used when determining the required reinforcement:

$$M^* = |M_{33}|$$

while the original sign of M_{33} is retained to identify the bending direction.

The design results are fundamentally expressed as:

$$A_{sT} = \text{required tension reinforcement}$$

and, where required:

$$A_{sC} = \text{required compression reinforcement}$$

This distinction is preferable to treating reinforcement intrinsically as "top" or "bottom", because the physical location of the tension face changes with the sign of the bending moment.

Consequently, the FEAKalc 3D graphical output can position the calculated tension reinforcement according to the sign of the corresponding bending-moment diagram.

2.1.7. Singly Reinforced Design

FEAKalc initially seeks a solution using tension reinforcement without requiring additional compression reinforcement.

For each candidate reinforcement arrangement, the program establishes the neutral axis from strain compatibility and force equilibrium and calculates the corresponding nominal moment resistance.

The section is acceptable where the resulting design flexural capacity satisfies:

$$\phi M_u \geq M^*$$

subject to the neutral-axis and reinforcement requirements incorporated into the flexural solver.

This approach means that the required steel is determined from the complete section equilibrium rather than solely from a closed-form expression such as $M = A_s f_y z$.

The same methodology is consistent with that used in the existing RK concrete beam calculation engine: a singly reinforced solution is sought first, and compression reinforcement is introduced where the required design action cannot be satisfied within the adopted neutral-axis limits.

2.1.8. Doubly Reinforced Design

Where the required bending resistance cannot be achieved satisfactorily as a singly reinforced section, FEAKalc introduces compression reinforcement.

The resulting section contains:

$$A_{sT}$$

on the tension side and:

$$A_{sC}$$

on the compression side.

Both reinforcement layers participate in the strain-compatibility calculation. Their respective stresses are therefore established from their positions relative to the neutral axis.

The force equilibrium becomes:

$$C_c + C_s = T_s + N_c$$

for the reinforced-concrete beam case, with the signs of the individual steel forces determined from the calculated strain state.

The compression reinforcement contribution is therefore explicitly incorporated into both force and moment equilibrium rather than being represented by an approximate additional moment capacity.

2.1.9. Strength Reduction Factor

The flexural strength reduction factor is determined within the detailed section calculation rather than applying one constant value to every beam section.

The calculated section state stores:

$$\phi$$

together with the nominal moment capacity:

$$M_u$$

and the design moment capacity:

$$\phi M_u$$

The strength reduction factor is associated with the calculated neutral-axis condition and hence with the ductility of the section.

This is important because sections approaching the limiting neutral-axis depth are not treated identically to sections possessing a substantially larger tensile strain.

2.1.10. Flexural Capacity

Once equilibrium has been established, FEAKalc determines the moment generated by the internal concrete and reinforcement forces about the selected reference axis.

The resulting nominal flexural resistance is:

$$M_u = \sum F_i z_i$$

where F_i represents each internal section force and z_i its corresponding lever arm.

The design capacity is then:

$$\phi M_u = \phi \, M_u$$

and the calculated capacity is returned for the particular design station.

The beam station result therefore contains both the applied action M^* and the calculated capacity ϕM_u, together with the required A_{sT} and A_{sC}.

2.1.11. Reinforcement Results Along the Beam

The calculation is repeated for each analysis station supplied to the beam design engine.

Accordingly, FEAKalc 3D obtains a reinforcement distribution of the form:

$$A_{sT}(x), \qquad A_{sC}(x)$$

rather than determining reinforcement at only one governing section.

For each beam, FEAKalc also identifies the governing flexural station from the maximum combined longitudinal reinforcement demand:

$$A_{s,\text{long}} = A_{sT} + A_{sC}$$

The station having the greatest value of this quantity is stored as the governing flexural station for the member.

For graphical presentation, the reinforcement demand may then be shown at the start, intermediate region and end of the member, with its position relative to the beam following the sign of the bending-moment diagram.

2.2. Shear Design Methodology

2.2.1. General

Beam shear design is performed at the same analysis stations used for flexural design.

For beams designed about local axis 3, FEAKalc uses the corresponding local shear:

$$V^* = |V_2|$$

The sign of shear is not required for determining the reinforcement quantity, and the absolute magnitude is therefore passed to the shear design routine.

The principal shear design output is:

$$\frac{A_{sv}}{s}$$

expressed as the required area of transverse shear reinforcement per unit spacing.

2.2.2. Effective Shear Depth

The longitudinal reinforcement effective depth is:

$$d = D - c$$

The effective shear depth used by the implementation is then:

$$d_v = \max(0.72D,\ 0.9d)$$

where D is the overall section depth.

This effective shear depth is used in calculating the applied shear stress and the shear resistance of the section.

2.2.3. Minimum Shear Reinforcement

The minimum shear reinforcement ratio implemented in the beam routine is:

$$\left(\frac{A_{sv}}{s}\right)_{\min} = \frac{0.2\, b_v}{f_{sy}}$$

where the effective transverse dimension b_v is taken by the implementation as:

$$b_v = \max(D - 2c,\ b - 2c)$$

and f_{sy} is the yield strength of the transverse reinforcement. The code identifies this internally as the minimum reinforcement requirement associated with Clause 8.2.1.7.

Where minimum shear reinforcement governs, the returned result is explicitly identified as a minimum reinforcement result, allowing FEAKalc to distinguish it from reinforcement governed directly by the applied shear demand.

2.2.4. Applied Shear Stress

For the present FEAKalc 3D beam implementation, torsion is not included in the shear design calculation.

The equivalent shear therefore reduces to the applied shear force V^*, and the corresponding shear stress is based on:

$$v^* = \frac{V^*}{b\, d_v}$$

with the appropriate unit conversion between kN and N.

The underlying routine contains provision for combined shear and torsion, but torsion is explicitly set to zero in the current implementation.

This distinction is important: although the finite element station retains the torsional action T^* as part of its analysis results, the present beam shear reinforcement calculation does **not** use that torsional action.

2.2.5. Longitudinal Strain and Shear Behaviour

The shear calculation calls the flexural design routine to obtain the longitudinal reinforcement associated with the section.

An estimate of longitudinal strain is then calculated and limited to:

$$\varepsilon_v \leq 0.003$$

with negative calculated values set to zero.

The concrete shear parameter k_v is subsequently evaluated as:

$$k_v = \frac{0.4}{1 + 1500\varepsilon_v}$$

The shear calculation therefore accounts for the influence of the longitudinal strain state rather than treating concrete shear resistance as a fixed value independent of flexural behaviour.

2.2.6. Shear Reinforcement Output

At each design station, FEAKalc returns the required transverse reinforcement in the form:

$$\frac{A_{sv}}{s}$$

together with calculated concrete and reinforcement shear-stress quantities.

The station result stores:

$$V^*, \qquad \frac{A_{sv}}{s}, \qquad v_c, \qquad v_s$$

and identifies whether the minimum shear reinforcement requirement governs.

Where the section cannot satisfy the implemented shear requirements, the routine returns a **Shear Failure**, which is converted to a failed beam shear design station.

2.2.7. Governing Shear Station

Because shear design is performed at each station, the transverse reinforcement demand varies along the member:

$$\frac{A_{sv}}{s} = f(x)$$

FEAKalc identifies the governing shear station as that having the maximum required value:

$$\left(\frac{A_{sv}}{s}\right)_{\max}$$

This station and the corresponding maximum transverse reinforcement demand are stored with the beam design result.

This provides the basis for displaying shear reinforcement requirements along the member independently of the flexural reinforcement results.

2.3. FE Model Integration and Beam Design Envelope

2.3.1. Beam Classification

Concrete frame members are not classified as beams from geometry alone. A member is designed as a beam only when its Concrete Design metadata explicitly identifies as as "Beam" (user may decide this by assigning design type). In the absence of an explicit beam designation, the concrete design workflow treats the member as a column. This preserves the behaviour of existing models until the user deliberately assigns a beam design type.

2.3.2. Design Stations

For each concrete beam, the FEAKalc integration layer extracts Moment3D results and creates three design stations: Start, Mid and End. Start and End correspond to the first and last analysis stations. Mid is located at the midpoint of the available station-coordinate range. Where an exact midpoint result is not present, N, M22, M33, V2, V3 and T are obtained by linear interpolation between the adjacent analysis stations.

The beam section design is therefore based on three representative locations along the member rather than every raw finite-element output point. These are the same Start, Mid and End locations presented in the concrete beam result table.

2.3.3. Load Combination Processing

Concrete beam design is repeated for every load combination whose name begins with LC-. Each combination is assembled from the stored load-case results using the user-defined combination factors. At a common frame station, the corresponding N, M22, M33, V2, V3 and T values are combined algebraically before the beam section calculation is performed.

2.3.4. Flexural and Shear Envelopes

The beam envelope is formed from design results rather than by first creating a single force envelope. At each of the Start, Mid and End stations, the governing flexural result is the load combination requiring the greatest total longitudinal reinforcement AsT + AsC. The governing shear result is selected independently as the load combination requiring the greatest Asv/s.

Consequently, the governing flexural and shear load combinations may differ from each other and may also differ between the Start, Mid and End stations. FEAKalc retains these governing load-combination names with the station results.

2.3.5. Selected-Member Design

When one or more frame members are selected in the model, only the selected eligible concrete members are submitted for design. When no frame member is selected, all eligible concrete beams are designed. This selection filter affects the members being checked, but does not alter the underlying structural analysis results.

3. Reinforced Concrete Column Design

3.1. Section Design Methodology

3.1.1. General

FEAKalc 3D performs reinforced concrete column assessment using axial force–moment interaction relationships generated from the specified section geometry, reinforcement arrangement, material strengths and member actions.

The present column design implementation applies to rectangular reinforced concrete columns with longitudinal reinforcement distributed around the section perimeter. The design is performed independently about the two principal section directions and is followed by a biaxial interaction assessment.

The principal inputs to the section calculation are:

$$f'_c, \quad f_y, \quad f_{ys}$$
$$b, \quad D, \quad c$$
$$L_e$$

together with the longitudinal bar diameter, number of bars along each face, axial actions and bending moments about the two principal axes.

The calculation produces:

- axial-force–moment interaction curves for both principal directions;
- squash load;
- moment magnification about both axes;
- amplified design moments;
- uniaxial utilisation about each principal direction; and
- biaxial interaction utilisation.

The column calculation memo also uses these calculated interaction curves directly to generate the graphical N-M and biaxial interaction diagrams.

3.1.2. Ultimate Axial Design Action

The column routine receives permanent and imposed axial actions separately.

The governing ultimate axial compression adopted by the implemented calculation is:

$$N^* = \max(1.2G + 1.5Q,\ 1.35G)$$

where:

G is the permanent axial action, and

Q is the imposed axial action.

This value is subsequently used throughout the column capacity, minimum eccentricity, slenderness and biaxial interaction calculations.

3.1.3. Concrete Stress-Block Parameters

The column interaction analysis uses concrete stress-block parameters dependent upon the specified compressive strength.

The first coefficient used in several parts of the column calculation is:

$$\alpha_1 = 1 - 0.003 f_c'$$

subject to:

$$0.72 \le \alpha_1 \le 0.85$$

A second concrete stress coefficient is:

$$\alpha_2 = 0.85 - 0.0015 f_c'$$

with:

$$\alpha_2 \ge 0.67$$

and the stress-block depth parameter is:

$$\gamma = 0.97 - 0.0025 f_c'$$

with:

$$\gamma \ge 0.67$$

These parameters are used directly by the implemented section solver when constructing the axial-force–moment interaction relationships.

The maximum concrete compressive strain adopted throughout the interaction analysis is:

$$\varepsilon_{cu} = 0.003$$

and the reinforcing steel modulus is:

$$E_s = 200\,000 \text{ MPa}$$

3.1.4. Longitudinal Reinforcement Arrangement

The rectangular column reinforcement is represented as bars distributed around the perimeter of the section.

If n_x is the number of bars distributed across the section width and n_y the number distributed across the section depth, the total number of perimeter bars is:

$$n_b = 2n_y + 2(n_x - 2)$$

For a specified bar diameter d_b, the individual bar area is:

$$A_b = \frac{\pi d_b^2}{4}$$

and the total longitudinal reinforcement area is:

$$A_s = n_b A_b$$

FEAKalc separately determines the reinforcement associated with the two opposite faces relevant to each bending direction so that the individual bar rows can be included in the strain-compatibility calculation.

The bars are assumed to be uniformly spaced between the specified cover locations.

For the width direction:

$$s_x = \frac{b - 2c}{n_x - 1}$$

and for the depth direction:

$$s_y = \frac{D - 2c}{n_y - 1}$$

This produces discrete reinforcement layers whose strains and forces are evaluated independently as the neutral axis changes.

3.1.5. Strain Compatibility

The interaction curves are generated by varying the neutral-axis parameter and calculating the corresponding concrete and reinforcement forces.

For a reinforcement layer located a distance x_i from the compression face, the implemented strain relationship may be expressed as:

$$\varepsilon_{si} = \frac{0.003}{k_u d}(k_u d - x_i)$$

where:

d is the appropriate effective section dimension for the bending direction, and

k_u defines the neutral-axis position relative to that dimension.

The reinforcement stress is then:

$$f_{si} = E_s \varepsilon_{si}$$

limited to:

$$-f_y \leq f_{si} \leq f_y$$

Compression reinforcement therefore develops positive compression stress, while reinforcement beyond the neutral axis develops tension stress.

FEAKalc does not assume that all longitudinal reinforcement has yielded. The stress in each reinforcement layer follows directly from its calculated strain.

3.1.6. Concrete Compression Force

For each trial neutral-axis position, the concrete compression resultant is calculated from the rectangular compression block.

For bending about one principal direction:

$$C_c = b_c \, \gamma k_u d \, f'_c \alpha$$

where b_c is the section dimension perpendicular to the bending direction.

The resultant acts at:

$$y_c = \frac{\gamma k_u d}{2}$$

from the compression face.

The calculation then adds the contribution of every reinforcement layer to obtain the section axial resistance:

$$N_u = C_c + \sum F_{si}$$

and the associated moment resistance is established by taking moments of the concrete and reinforcement forces about the section centre.

Accordingly, each interaction-curve point represents a section state satisfying the adopted linear strain distribution and internal force equilibrium.

3.1.7. Squash Load

The design axial compression capacity at essentially concentric loading is calculated independently as the column squash load.

The implemented expression is:

$$\phi N_{uo} = 0.6\left[\alpha_1 f_c'(A_g - A_s) + A_s f_y\right]$$

with the appropriate conversion to kN.

Here:

$$A_g = bD$$

is the gross section area.

The strength reduction factor used for this squash-load condition is therefore:

$$\phi = 0.6$$

in the present FEAKalc column implementation.

This squash-load value forms the compression end of both uniaxial interaction curves.

3.2. Uniaxial Interaction Curves

3.2.1. General

FEAKalc generates two independent axial-force–moment interaction relationships:

$$N - M_{22}$$

and:

$$N - M_{33}$$

These correspond to bending about the two principal directions of the rectangular section.

For each direction, the program varies the neutral-axis position and calculates:

$$\phi N_u$$

and:

$$\phi M_u$$

from the concrete and reinforcement forces.

The resulting collection of calculated points forms the design interaction curve used for both graphical output and utilisation assessment.

3.2.2. Weak-Axis Interaction Curve

For the first principal direction, the relevant effective dimension is:

$$d_{22} = b - c$$

in the implemented calculation.

At each trial k_u, the concrete compression force is determined together with the strain and stress in each reinforcement layer distributed across the section width.

The total axial resistance is:

$$N_u = C_c + \sum F_s$$

and the corresponding moment is calculated from the internal forces relative to the section centre.

The interaction curve begins at the squash-load point:

$$(M, N) = (0, \phi N_{uo})$$

and proceeds progressively through combined compression and bending towards the lower-axial-load and bending-dominated region.

3.2.3. Strong-Axis Interaction Curve

The second principal direction is assessed using the same fundamental strain-compatibility procedure, but with the section dimensions and reinforcement arrangement rotated accordingly.

The effective dimension becomes:

$$d_{33} = D - c$$

and the reinforcement layers are evaluated at their locations through the section depth.

The calculated strong-axis curve likewise begins at:

$$(0, \phi N_{uo})$$

and progresses through the combined axial force–moment domain.

Where the section is square and has the same number of bars in each direction, the implementation aligns the initial interaction-curve parameter between the two directions, reflecting the geometric symmetry of the section.

3.2.4. Strength Reduction Factor Along the Curve

The interaction curves do not use a constant ϕ throughout their complete length.

In the compression-controlled portion of the curve, FEAKalc adopts:

$$\phi = 0.6$$

As the neutral axis moves towards the compression face and the section enters a more tension-controlled condition, the program progressively increases ϕ.

The implemented procedure allows the strength reduction factor to increase towards:

$$\phi = 0.85$$

for the lower axial-load portion of the interaction curve.

This creates a transition from compression-dominated behaviour towards bending-dominated behaviour as the section ductility increases.

3.2.5. High-Strength Concrete Confinement Region

For:

$$f_c' > 50 \text{ MPa}$$

the source implementation also generates additional confinement-related curve data.

These points are stored separately from the primary interaction curves and are intended to be superimposed on the interaction diagram.

The current implementation therefore contains an explicit additional treatment for concrete strengths exceeding 50 MPa rather than treating these sections identically to lower-strength concrete throughout the complete interaction diagram.

3.3. Minimum Eccentricity and Design Moments

3.3.1. Minimum Eccentricity

Before the column moments are used for slenderness and interaction assessment, FEAKalc applies a minimum eccentricity requirement.

For the first bending direction:

$$e_{\min,22} = 0.05b$$

and:

$$M_{\min,22} = N^* e_{\min,22}$$

Similarly, for the second direction:

$$e_{\min,33} = 0.05D$$

and:

$$M_{\min,33} = N^* e_{\min,33}$$

with dimensions converted from millimetres to metres when calculating the corresponding moment in kNm.

The adopted end moments are therefore not allowed to fall below the moment generated by a 5% section-dimension eccentricity.

This minimum eccentricity is applied separately about each principal direction.

3.3.2. End-Moment Selection

For each direction, FEAKalc determines:

$$M_1 = \min(|M_{\text{top}}|,\ |M_{\text{bottom}}|)$$

and:

$$M_2 = \max(|M_{\text{top}}|,\ |M_{\text{bottom}}|)$$

subject to the minimum eccentricity described above.

The relative sign of the end moments is retained to distinguish between single-curvature and double-curvature bending.

Where the two end moments have opposite signs, the sign of the governing M_2 value is adjusted within the calculation so that the moment-gradient coefficient reflects the double-curvature condition.

3.4. Slenderness and Moment Magnification

3.4.1. General

FEAKalc accounts for member slenderness using a moment-magnification procedure.

The calculation is undertaken independently for the two principal bending directions using the member effective length associated with each axis.

The effective lengths are supplied from the FEAKalc 3D member design data, either from automatically determined values or from user-defined effective-length settings.

For the column section calculation, the governing column height is based on the applicable effective member length used by the design procedure.

3.4.2. Moment Gradient Coefficient

For each principal direction the moment-gradient coefficient is calculated as:

$$k_m = 0.6 - 0.4\frac{M_1}{M_2}$$

subject to:

$$k_m \geq 0.4$$

The sign of M_1/M_2 therefore allows the calculation to distinguish between single- and double-curvature bending.

The same procedure is carried out independently for the second principal direction.

3.4.3. Critical Axial Load

The implementation calculates an effective critical axial load from the member height and a section stiffness quantity derived from the calculated balanced moment.

For the first principal direction, the implemented relationship has the form:

$$N_c = \frac{\pi^2}{L_e^2}\frac{182\,d\,(\phi M_{ub})\,10^6}{1000(1+\beta_d)}$$

where:

$$\beta_d = \frac{G}{G+Q}$$

when $G + Q \neq 0$.

A corresponding calculation is performed for the orthogonal direction using its appropriate section dimension and balanced moment capacity.

The factor **182** is explicitly part of the current FEAKalc implementation. It should therefore be documented as part of the implemented design methodology rather than replaced by a more generic stiffness expression.

3.4.4. Moment Magnification Factor

The magnification factor is calculated as:

$$\delta_b = \frac{k_m}{1 - N^*/N_c}$$

Where a positive calculated value is less than unity, FEAKalc sets:

$$\delta_b = 1$$

so that slenderness cannot reduce the design moment.

A non-positive calculated condition is treated separately by the implementation and effectively indicates that a usable normal magnification factor has not been obtained.

The amplified design moment is then:

$$M^*_{d,22} = |\delta_{b,22} M_{2,22}|$$

and:

$$M^*_{d,33} = |\delta_{b,33} M_{2,33}|$$

These magnified moments are the moments subsequently used in the uniaxial and biaxial column checks.

3.5. Uniaxial Utilisation

3.5.1. Interaction-Curve Assessment

For each principal direction, FEAKalc compares the design action point:

$$(N^*, M_d^*)$$

with the calculated interaction curve.

Rather than simply comparing the applied moment with a single interpolated capacity at N^*, the current implementation searches the generated interaction curve for a point having approximately the same radial slope from the origin as the design action.

For the design action:

$$L_d = \sqrt{(N^*)^2 + (M_d^*)^2}$$

A corresponding capacity-vector length is obtained from the interaction curve:

$$L_c = \sqrt{N_c^2 + M_c^2}$$

and the uniaxial demand/capacity ratio is then:

$$\mathrm{DCR} = \frac{L_d}{L_c}$$

The procedure is performed independently for the two principal directions.

3.5.2. Numerical Search Procedure

The current implementation searches for an interaction-curve point whose slope is sufficiently close to the design-action slope.

The initial search tolerance is approximately:

$$0.95 \le \frac{s_{\text{design}}}{s_{\text{curve}}} \le 1.05$$

If no suitable point is found, the search band is progressively widened.

This is an implementation-specific numerical procedure used to obtain the uniaxial utilisation from the discretely generated interaction curve. It is therefore appropriate for the methodology manual to explain that the DCR is calculated numerically from the generated curve rather than implying an exact closed-form intersection.

3.6. Biaxial Design

3.6.1. General

After completing the two uniaxial interaction assessments, FEAKalc performs a biaxial bending check using the moment capacities corresponding to the applied axial compression.

The procedure combines the amplified moments about the two principal directions:

$$M_{22}^*$$

and:

$$M_{33}^*$$

with the available uniaxial moment capacities at the same axial load.

3.6.2. Biaxial Interaction Exponent

The biaxial interaction exponent is calculated by the implementation as:

$$\alpha_b = 0.7 + 1.7\frac{N^*/0.65}{N_{uo}/0.6}$$

where N_{uo} corresponds to the design squash-load value used by the calculation.

The resulting exponent is restricted to:

$$1.0 \leq \alpha_b \leq 2.0$$

Consequently, the shape of the biaxial interaction relationship changes with the level of axial compression.

3.6.3. Biaxial Interaction Equation

The implemented biaxial utilisation is:

$$U_b = \left(\frac{M_{22}^*}{M_{u,22}}\right)^{\alpha_b} + \left(\frac{M_{33}^*}{M_{u,33}}\right)^{\alpha_b}$$

where the design moments include the respective moment magnification factors.

In terms of the actual program variables, the denominators are derived from the calculated uniaxial capacities corresponding to the applied axial force and include the strength-reduction treatment used by the column engine.

The column satisfies the biaxial interaction check when:

$$U_b \leq 1.0$$

and fails the biaxial interaction check when:

$$U_b > 1.0$$

The calculated U_b is returned as one of the principal column utilisation results.

3.6.4. Biaxial Interaction Diagram

FEAKalc also generates a graphical interaction curve in M_{22}-M_{33} space.

For a selected axial load, the curve is defined from the two corresponding uniaxial moment capacities and the calculated exponent α_b.

Conceptually:

$$\left(\frac{M_{22}}{M_{u,22}}\right)^{\alpha_b} + \left(\frac{M_{33}}{M_{u,33}}\right)^{\alpha_b} = 1$$

The program generates a sequence of points between:

$$(0, M_{u,33})$$

and:

$$(M_{u,22}, 0)$$

and plots the actual design point:

$$(M_{22}^*, M_{33}^*)$$

on the same diagram.

This allows the calculation memo to show directly whether the applied biaxial moment combination lies inside or outside the calculated design interaction envelope.

3.7. Design Acceptance

The rectangular column calculation returns three principal utilisation measures:

$$U_{22}$$

for the first uniaxial interaction check,

$$U_{33}$$

for the second uniaxial interaction check, and

$$U_b$$

for biaxial interaction.

The column is considered satisfactory only where the relevant interaction and stability calculations produce valid results and the utilisation values do not exceed unity.

The optimisation logic in FEAKalc explicitly rejects a trial section where:

$$\delta_{b,22} \leq 0$$

or:

$$\delta_{b,33} \leq 0$$

or where any of:

$$U_{22} > 1, \qquad U_{33} > 1, \qquad U_b > 1$$

occurs.

This is important because the column assessment is not governed solely by the biaxial check. A section must also remain valid under each principal-direction assessment and the implemented slenderness procedure.

3.8. Automatic Reinforcement Optimisation

3.8.1. General

FEAKalc 3D includes an automatic optimisation routine for rectangular reinforced concrete columns. The current implementation is intended primarily to determine a practical reinforcement arrangement for a user-specified rectangular section while targeting a utilisation below the design limit.

The optimisation procedure uses the same rectangular column interaction engine described previously. Trial reinforcement arrangements are therefore assessed using the same axial-force, moment magnification, uniaxial interaction and biaxial interaction calculations as the normal column design routine.

The present implementation contains two optimisation modes:

MinReo

and:

MinDim

However, the source code identifies the minimum-dimension routine as not yet mature and not used for the current workflow. The presently relevant optimisation procedure is therefore the **minimum reinforcement mode for a fixed rectangular section**.

3.8.2. Fixed Section Geometry

For the minimum-reinforcement optimisation mode, the user supplies the column width and depth.

The dimensions are first restricted to a minimum of:

200 mm

and then rounded **upwards** to the next 25 mm increment:

$$b_{\text{adopted}} = 25\left\lceil \frac{b}{25} \right\rceil$$
$$D_{\text{adopted}} = 25\left\lceil \frac{D}{25} \right\rceil$$

The optimisation therefore does not reduce the dimensions entered by the user and avoids returning dimensions that are smaller than the specified section.

The reinforcement search is subsequently performed for this adopted section.

3.8.3. Effective Member Length Used for Optimisation

The optimisation request includes member length together with effective lengths about both principal directions.

For each direction, FEAKalc applies the following hierarchy:

$$L_{e22} = \begin{cases} \text{specified effective length,} & L_{e22} > 0 \\ \text{automatic effective length,} & \text{otherwise} \\ \text{member length,} & \text{otherwise} \end{cases}$$

and similarly:

$$L_{e33} = \begin{cases} \text{specified effective length,} & L_{e33} > 0 \\ \text{automatic effective length,} & \text{otherwise} \\ \text{member length,} & \text{otherwise} \end{cases}$$

For the section optimisation calculation, the governing column height is then taken as:

$$L_e = \max(L_{e22}, L_{e33})$$

This is the height subsequently passed to the rectangular column interaction and moment-magnification calculation.

The resulting optimisation output retains the individual effective lengths and their corresponding modes for later use by the FEAKalc 3D design interface.

3.8.4. Minimum Design Eccentricity During Optimisation

Before reinforcement optimisation is undertaken, FEAKalc compares the analysis moment with a minimum moment derived from axial load eccentricity.

For the weaker section direction:

$$e_{22} = 0.05\min(b, D)$$

and for the stronger section direction:

$$e_{33} = 0.05\max(b, D)$$

The minimum moments are:

$$M_{22,\min} = N^* \frac{e_{22}}{1000}$$

and:

$$M_{33,\min} = N^* \frac{e_{33}}{1000}$$

The actual moments used for optimisation are:

$$M_{22} = \max\left(|M_{22,\text{analysis}}|, M_{22,\min}\right)$$

and:

$$M_{33} = \max\left(|M_{33,\text{analysis}}|, M_{33,\min}\right)$$

Accordingly, a column with very small first-order analysis moments is not optimised as a purely concentric member.

3.8.5. Target Utilisation

The reinforcement optimiser seeks a design utilisation of approximately:

$$U_{\text{target}} = 0.85$$

with a numerical tolerance of:

$$\pm 0.02$$

The utilisation used by the search is the maximum of:

$$U_{22}, \qquad U_{33}, \qquad U_b$$

provided the moment-magnification factors remain valid.

If either magnification factor is non-positive, or if any interaction utilisation exceeds unity during a trial design, the routine treats the trial as an unacceptable design condition.

The choice of approximately 85% rather than 100% utilisation provides reserve capacity within the automatically selected reinforcement arrangement.

3.8.6. Reinforcement Percentage Search

For a fixed rectangular section, FEAKalc searches for a suitable reinforcement percentage using a binary-search procedure.

The present search bounds are:

$$1.0\% \le \rho_s \le 10.0\%$$

where the percentage is defined as:

$$\rho_s = \frac{A_s}{bD} \times 100$$

The source comments around these bounds contain older notes that do not match the actual numerical values; the implemented search itself uses 1% and 10%, and these are the values that should be documented.

A trial reinforcement percentage is evaluated using the complete column design engine.

If:

$$U > U_{\text{target}}$$

the trial section requires additional reinforcement and the lower search bound is increased.

If:

$$U < U_{\text{target}}$$

the trial contains more reinforcement than required for the target and the upper bound is reduced.

The process is repeated for up to 35 iterations, or until:

$$|U - U_{\text{target}}| \le 0.02$$

The final reinforcement percentage is then passed to the reinforcement-layout selection routine.

3.9. Selection of Practical Reinforcement

3.9.1. General

The optimiser does not return reinforcement percentage alone. Once a target percentage has been established, FEAKalc selects an actual bar diameter and number of perimeter bars that provide at least the required reinforcement area while satisfying the spacing limits implemented by the routine.

This produces a discrete reinforcement arrangement suitable for subsequent column design and display.

3.9.2. Available Bar Diameters

The search begins with the user-specified target bar diameter and may then consider:

$$16,\ 20,\ 24,\ 28,\ 32,\ 40\ \text{mm}$$

The user-selected diameter is placed first in the search list, so the optimisation preferentially attempts to satisfy the reinforcement requirement using that diameter before testing the remaining available sizes.

For a selected diameter d_b:

$$A_b = \frac{\pi d_b^2}{4}$$

3.9.3. Bar Spacing Limits

The implemented reinforcement-layout search uses:

$$s_{\text{min}} = 50\ \text{mm}$$

and:

$$s_{\text{max}} = 250\ \text{mm}$$

for bar spacing along each face.

For n_x bars along the width:

$$s_x = \frac{b - 2c}{n_x - 1}$$

and for n_y bars along the depth:

$$s_y = \frac{D - 2c}{n_y - 1}$$

A trial reinforcement pattern is rejected unless:

$$50 \le s_x \le 250$$

and:

$$50 \le s_y \le 250$$

The current automatic column design routine therefore uses these spacing limits as explicit practical constraints during reinforcement selection.

3.9.4. Perimeter Reinforcement

For each trial combination of n_x and n_y, the total number of perimeter bars is:

$$n_b = 2n_y + 2(n_x - 2)$$

and the resulting reinforcement area is:

$$A_s = n_b A_b$$

The actual reinforcement percentage is then:

$$\rho_s = \frac{A_s}{bD} \times 100$$

The first arrangement encountered for which:

$$\rho_s \geq \rho_{s,\text{target}}$$

and which satisfies the spacing limits is adopted by the routine.

Because the layout uses discrete bar sizes and whole numbers of bars, the actual reinforcement percentage may be higher than the theoretical percentage determined by the preceding binary search.

3.9.5. Returned Optimised Column Properties

For each successfully optimised rectangular column, FEAKalc returns the adopted:

$$b, \quad D, \quad d_b, \quad n_x, \quad n_y$$

together with:

$$f_c', \quad f_y, \quad c$$

and the actual reinforcement percentage.

The result also retains:

$$L, \quad L_{e22}, \quad L_{e33}$$

the automatic effective lengths, effective-length modes and factors, and the corresponding ratios:

$$\beta_{22} = \frac{L_{e22}}{L}$$
$$\beta_{33} = \frac{L_{e33}}{L}$$

where a valid member length is available.

This allows the optimised design to be passed back into the FEAKalc 3D interface without losing the stability assumptions associated with the member.

3.10. FE Model Integration and Column Design Envelope

3.10.1. Column Classification and Selection

A concrete frame is treated as a column whenever it is not explicitly designated as a beam in its ConcreteDesign metadata. If one or more frame members are selected, the column design request is limited to the selected eligible concrete columns; if nothing is selected, all eligible concrete columns are checked.

3.10.2. Column Action Extraction

For each LC-* combination, the column integration layer uses all Moment3D stations for the member. The axial action is the maximum absolute N value found along the member. The two end M22 values are used as the weak-direction end moments, while the two end M33 values are used as the strong-direction end moments. These actions are passed to the column optimiser for that specific load combination.

3.10.3. Effective-Length Resolution

Before any selection filter is applied to the design members, FEAKalc builds the automatic effective-length map from the complete structural model. This is intentional: restraint and continuity calculations remain based on the full model even when the user chooses to design only selected members.

For each axis, the effective length is then resolved from one of three modes. In Auto mode, the program-determined effective length is used, falling back to the physical member length where necessary. In Factor mode, the effective length is the physical member length multiplied by the user-specified K factor. In Length mode, the user-specified effective length is used directly. The resolved values are retained separately for directions 22 and 33 together with the corresponding beta ratios Le/L.

3.10.4. Column Load-Combination Envelope

The rectangular-column optimisation is performed independently for every LC-* combination. The front-end envelope then retains, for each column, the result that requires the greatest longitudinal reinforcement percentage. The load combination associated with that reinforcement requirement is stored as the governing column load case.

This is an important implementation detail: the column envelope is selected by required reinforcement percentage, not by simply taking the largest axial force, largest moment or largest displayed interaction utilisation from different combinations and combining them artificially.

3.10.5. Section Geometry and Concrete Eligibility

Only frame members whose material metadata identifies them as concrete, RC or reinforced concrete are eligible for the concrete design workflow. Rectangular dimensions may be read from explicit ConcreteDesign width/depth metadata or parsed from section names of the form b x D. Circular geometry can be recognised by the integration layer, but the current column optimisation branch for circular sections remains incomplete and is not part of the supported design scope.

4. Design Results

4.1. General

The concrete design module returns member-level results together with station-level data.

Beam results are stored separately from column results because the design quantities and governing criteria differ substantially.

For beams, the principal design quantities are required longitudinal and shear reinforcement.

For columns, the principal result is utilisation under combined axial force and bending.

4.2. Beam Flexural Results

At each beam station, FEAKalc stores:

$N^* \; M^* \; V^* \; T^*$

together with:

$\phi M_u \; A_{sT}$

and:

$$A_{sC}$$

The flexural result is reported as passing where a valid section solution is obtained and the required reinforcement remains within the maximum reinforcement limits used by the beam solver.

Where no acceptable section solution can be obtained, the flexural result is returned as a failure.

The user-facing reinforcement result is therefore preferably presented as:

$$A_{sT} = \text{required tension reinforcement}$$

and, where non-zero:

$$A_{sC} = \text{required compression reinforcement}$$

rather than permanently labelling reinforcement as top or bottom.

4.3. Beam Shear Results

At each beam station, the shear result contains:

$$\frac{A_{sv}}{s}$$

together with the calculated concrete and supplementary shear-stress quantities.

Where minimum transverse reinforcement governs, this condition is retained separately in the result.

If the applied shear stress exceeds the implemented maximum shear capacity, the station is identified as:

Shear Failure

and the beam station is reported as failed.

4.4. Governing Beam Results

For flexure, FEAKalc determines the governing station from the maximum total longitudinal reinforcement:

$$A_{s,\text{total}} = A_{sT} + A_{sC}$$

For shear, the governing station is that having the maximum:

$$\frac{A_{sv}}{s}$$

The overall beam status is:

PASS where all design stations pass,

FAIL where any station fails, and

Skipped where no valid station design has been produced.

4.5. Column Results

For columns, FEAKalc retains the governing optimisation result from the LC-* envelope together with its governing load-combination name, adopted reinforcement arrangement, reinforcement percentage, effective lengths and the actions required to reproduce the column calculation memo.

In the current FEAKalc 3D result table, the overall column PASS/FAIL display is based on the adopted longitudinal reinforcement percentage: reinforcement up to and including 4.0% is displayed as PASS and reinforcement above 4.0% as FAIL. This interface criterion is separate from the uniaxial and biaxial utilisation checks performed inside the section calculation and optimisation routine.

The result table also reports the governing LC-* combination and the selected perimeter bar arrangement. The colour scale used for the model display varies from green at approximately 1% reinforcement to red at 4% reinforcement.

4.6. Calculation Memo and Interaction Diagrams

4.6.1. General

The FEAKalc 3D column calculation memo presents the numerical column design together with interaction diagrams generated directly from the design engine.

The memo receives the calculated weak-axis, strong-axis and biaxial interaction data and converts these data into graphical SVG output.

The graphics therefore represent the same calculated interaction points used by the design engine rather than independent illustrative curves.

4.6.2. Uniaxial Interaction Diagrams

For each principal direction, the memo plots:

$$\phi N_u$$

against:

$$\phi M_u$$

The applied design point:

$$(N^*, M^*)$$

is plotted on the same diagram.

The graphical routine determines the plotting range from both the calculated interaction curve and the applied design actions, allowing the demand point to remain visible where it approaches or exceeds the calculated envelope.

The two diagrams therefore provide a direct visual representation of the column capacity about each principal axis.

4.6.3. Biaxial Interaction Diagram

The biaxial memo plots:

$$M_{22}$$

against:

$$M_{33}$$

for the interaction boundary corresponding to the applied axial load.

The applied biaxial moment point:

$$(M_{22}^{*}, M_{33}^{*})$$

is then superimposed on the calculated interaction curve.

A demand point located inside the envelope corresponds to:

$$U_b \leq 1$$

while a point outside the envelope corresponds to a biaxial utilisation greater than unity.

5. Design Assumptions and Current Limitations

5.1. General

The concrete design methodology described in this document reflects the current FEAKalc 3D implementation.

Where functionality is present in the underlying source code but is not presently active in the FEAKalc 3D workflow, it should not be interpreted as fully supported design functionality.

5.2. Beam Section Types

The current FEAKalc 3D concrete beam workflow is intended for rectangular sections.

The underlying flexural engine contains general T-beam geometry, but the FEAKalc 3D beam call currently supplies:

$$b_f = b_w$$

and effectively uses the rectangular case.

Accordingly, T-beam and L-beam design should not be claimed as part of the present FEAKalc 3D concrete frame module unless the user interface and section transfer are subsequently extended to provide the required flange geometry.

5.3. Beam Design Axes

The current beam routine designs flexure using:

$$M_{33}$$

with corresponding shear:

$$V_2$$

The orthogonal bending/shear pair is not separately designed by the present beam workflow.

This assumption is appropriate for normal beam orientation where the local 3-axis corresponds to the primary flexural direction, but the member local axes should be reviewed when non-standard section orientations are used.

5.4. Beam Torsion

Although torsional action is recovered from the finite element model and stored with the beam station results, the present concrete shear design routine sets torsion to zero.

Therefore:

$$T^*$$

is **not presently included** in the beam transverse reinforcement design.

The current beam design results should consequently not be interpreted as a combined shear-and-torsion reinforcement design.

5.5. Reinforcement Allowance in Beam Design

After the required tension and compression reinforcement has been determined, the current beam flexural routine increases the reported reinforcement by 10%.

Consequently, the reinforcement returned to FEAKalc is:

$$A_{sT,\text{reported}} = 1.10 A_{sT,\text{calc}}$$

and:

$$A_{sC,\text{reported}} = 1.10 A_{sC,\text{calc}}$$

where compression reinforcement is required.

This is an implementation-specific reinforcement allowance and should be identified in the manual rather than presented as part of the fundamental equilibrium equations.

5.6. Column Section Types

The implemented column interaction engine described in this manual applies to rectangular reinforced concrete columns.

The optimisation code is currently targeting rectangular columns (as of 10/8/2026)

5.7. Effective Length

The column design results depend directly on the effective length supplied to the design engine.

FEAKalc 3D may determine these lengths automatically or accept user-defined values. The concrete section solver subsequently uses the resulting effective member height in its slenderness and moment-magnification calculations.

The reliability of the amplified design moments therefore depends on an appropriate effective-length representation of the actual structural restraint conditions.

5.8. Numerical Interaction Curves

The column interaction curves are generated numerically from a sequence of neutral-axis positions rather than from a closed-form interaction equation.

The uniaxial DCR search subsequently finds an approximately corresponding point on this discrete curve using a slope-tolerance procedure.

Small numerical differences may therefore arise depending upon the interaction-curve discretisation and the numerical search procedure.

6. Overall Concrete Design Workflow

The complete FEAKalc 3D concrete design process may be summarised as follows.

- Structural model
- Finite element analysis
- Recovery of frame actions
- $N,\ M_{22},\ M_{33},\ V_2,\ V_3,\ T$
- Classify frame as beam or column
- For a **beam**:
    - M_{33}, V_2, N
    - Flexural strain compatibility
    - Determine:
    - $A_{sT}, A_{sC}, \phi M_u$
    - Shear assessment
    - Determine:
    - A_{sv}/s
    - Report reinforcement along member.
- For a **column**:
    - $N, M_{22}, M_{33}, L_{e22}, L_{e33}$
    - Minimum eccentricity
    - Moment magnification
    - Generate:
    - $N - M_{22}$
    - interaction curve
    - Generate:
    - $N - M_{33}$
    - interaction curve
    - Determine uniaxial utilisations
    - Perform biaxial interaction check
    - Report governing column utilisation and interaction diagrams.

7. Summary

FEAKalc 3D integrates reinforced concrete member design with the force results obtained directly from its three-dimensional finite element analysis.

Concrete beams are assessed station-by-station for flexure and shear. Flexural reinforcement is determined using strain compatibility, force equilibrium and a concrete compression block, with compression reinforcement introduced where a singly reinforced section cannot satisfy the required moment. The resulting reinforcement is reported as tension reinforcement A_{sT} and, where required, compression reinforcement A_{sC}. Shear reinforcement is determined independently as A_{sv}/s.

Rectangular concrete columns are analysed using generated axial-force–moment interaction curves about both principal directions. The calculation incorporates minimum eccentricity, member effective length, moment magnification and a biaxial interaction relationship. The same section engine is used by the automatic reinforcement optimiser, allowing practical perimeter reinforcement arrangements to be selected against the calculated column demand.

The resulting methodology provides a direct connection between the FEAKalc 3D structural model and the reinforced concrete design results presented to the engineer, while retaining sufficient section-level information to generate detailed calculation memos and interaction diagrams.

Appendix – A

Verification Example and Concrete Design workflow

Verification example - FEAKalc 3D vs. ETABS

The frame was analysed in both FEAKalc 3D and ETABS using identical geometry, loading, member properties and support conditions. All members are 600 × 600 mm concrete sections, with fc =40 MPa and E=28,000 MPa.

The comparison shows very close agreement between the two programs:

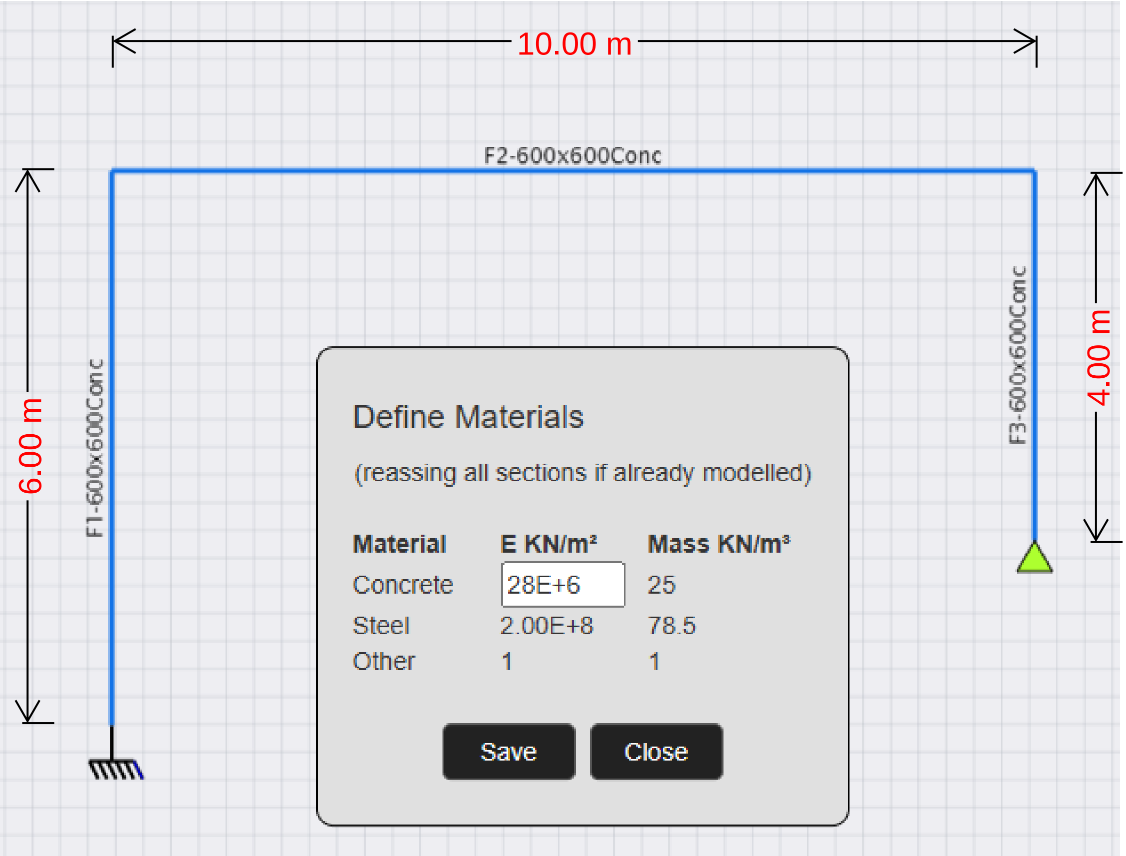
1- Bending moments, shear forces and axial forces are essentially identical throughout the frame.

2- The maximum beam sagging moment is 490.36 kNm in FEAKalc 3D, compared with 490.73 kNm in ETABS (agreement within 0.075 %)

3- The principal joint and column forces generally match to the displayed precision.

4- At the upper-right joint, both programs calculate a horizontal displacement of 1.682 mm and a vertical displacement of -0.165 mm (identical)

Overall, the example demonstrates excellent correlation between FEAKalc 3D and ETABS for frame actions and nodal displacements.



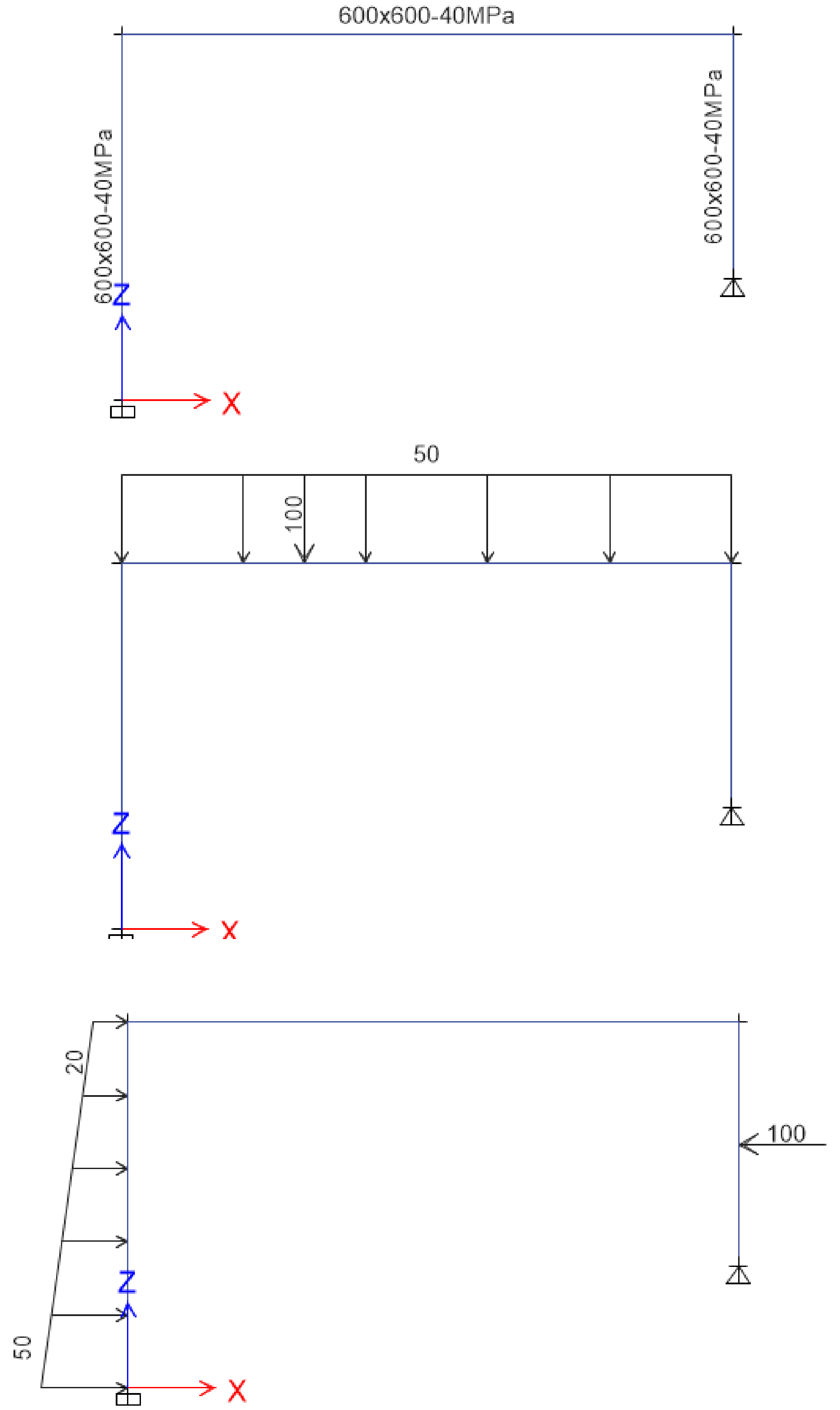
LEARNING CENTRE

RKALC

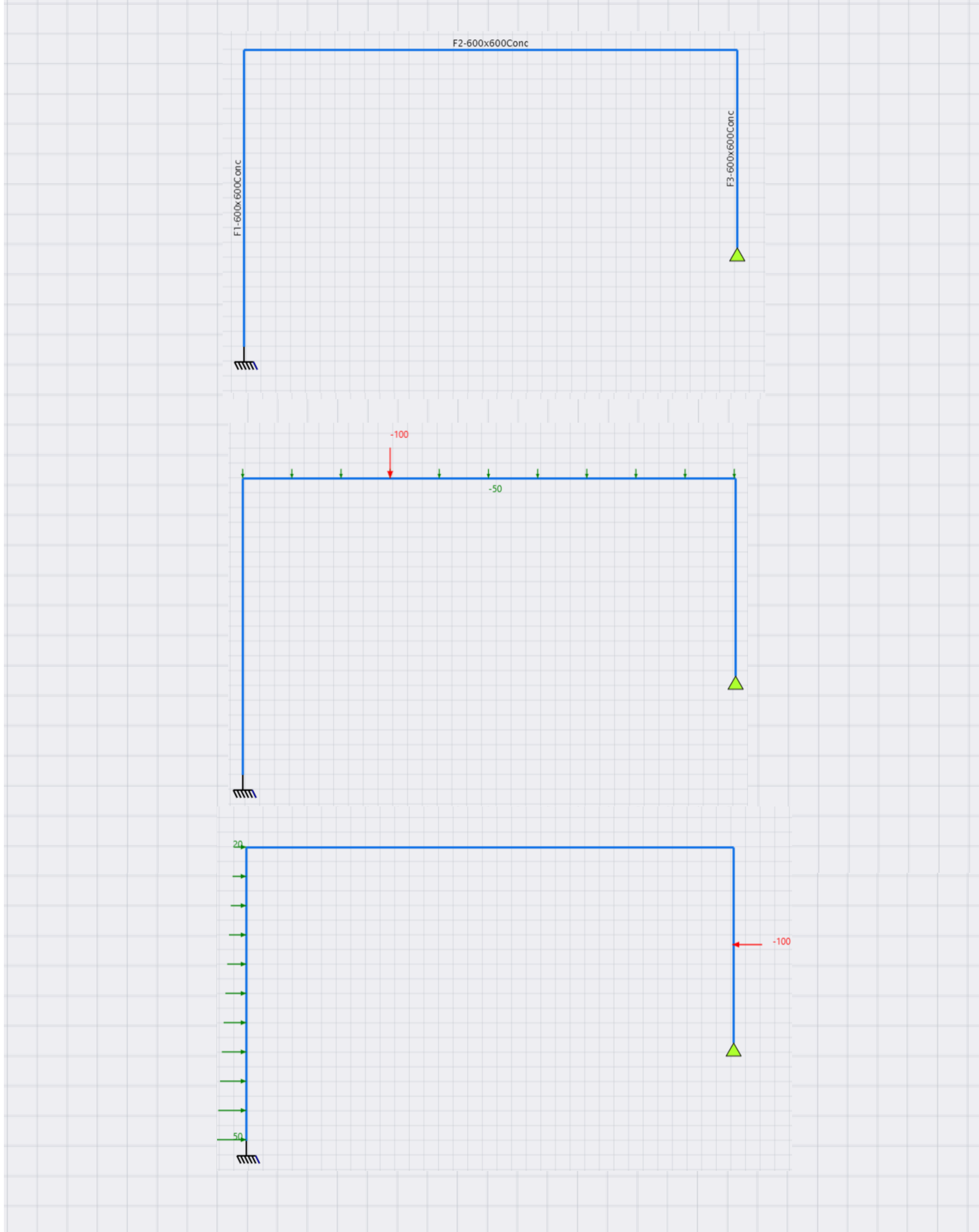
Analysis Verification

Concrete Frame	By	RK
FEAKalc 3D Verifications	Sheet No. 2	Date 7/26

ETABS



FEAKalc 3D

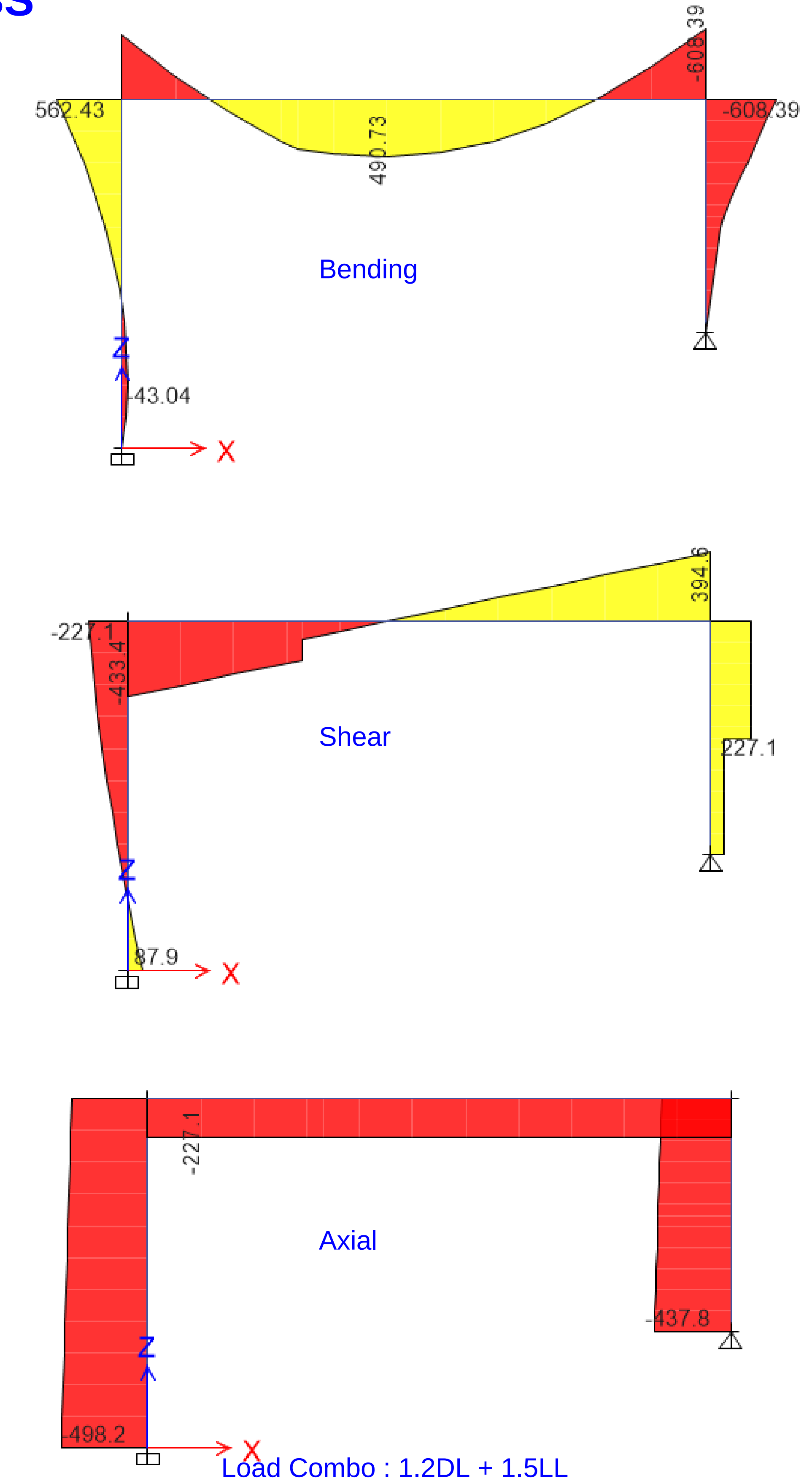


LEARNING CENTRE
RKALC

Analysis Verification

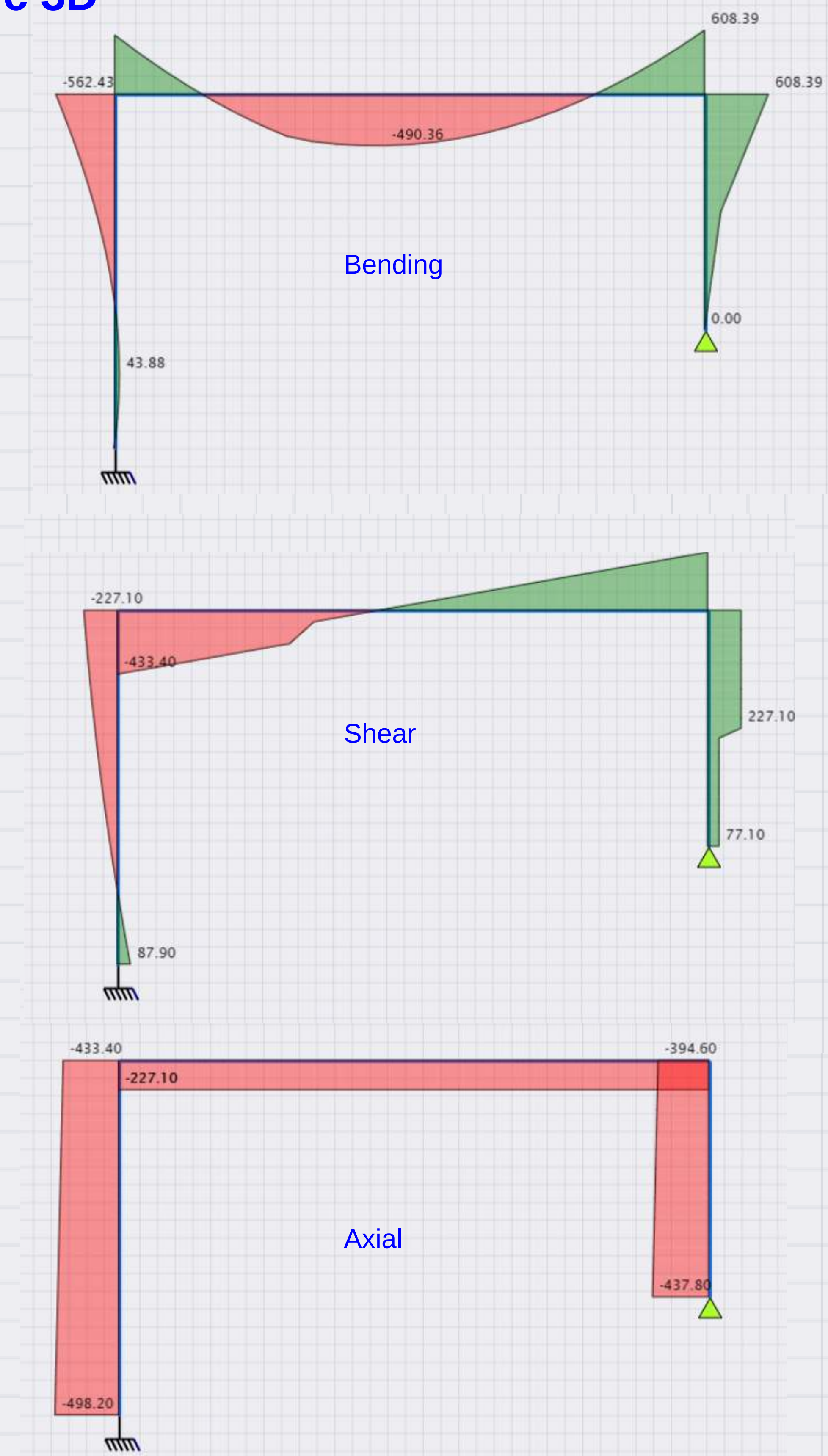
Concrete Frame	By	RK
FEAKalc 3D Verifications	Sheet No. 3	Date 7/26

ETABS



Load Combo : 1.2DL + 1.5LL

FEAKalc 3D

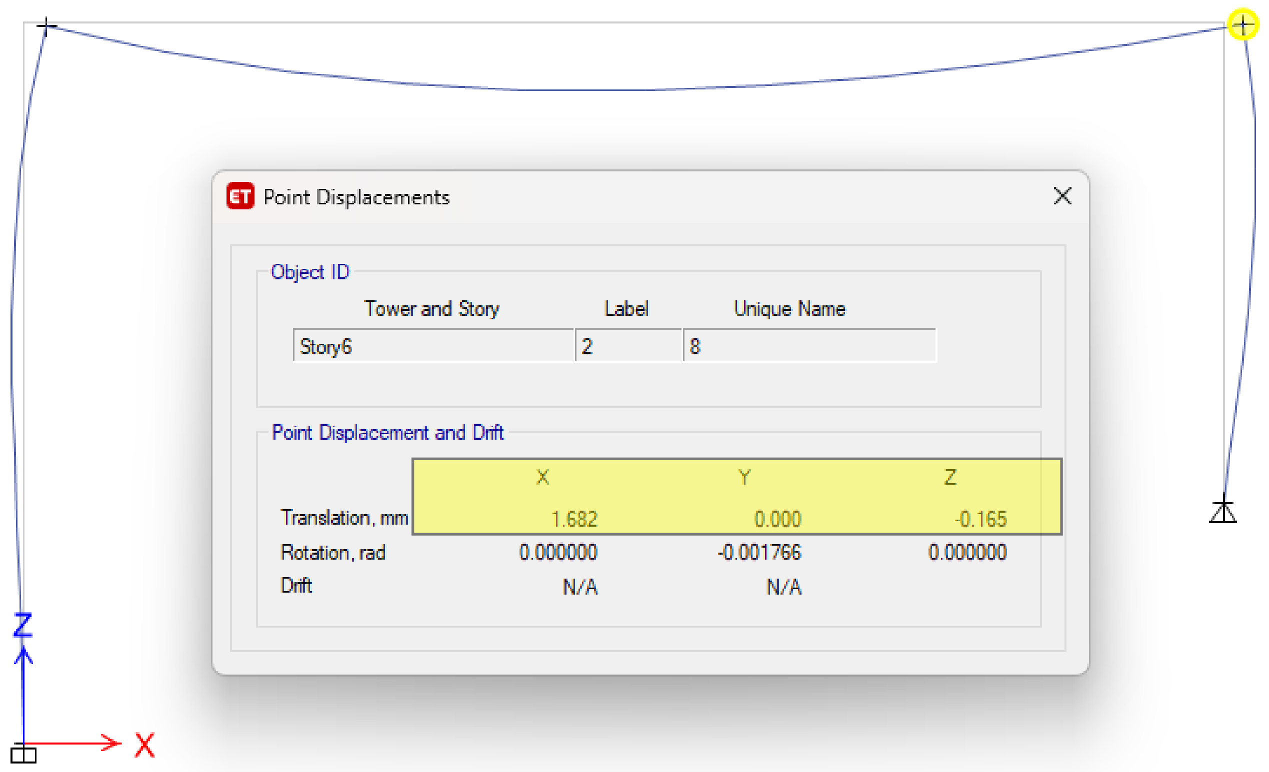


Load Combo : 1.2DL + 1.5LL

LEARNING CENTRE	Analysis Verification	Concrete Frame	By	RK
		FEAKalc 3D Verifications	Sheet No. 4	Date 7/26

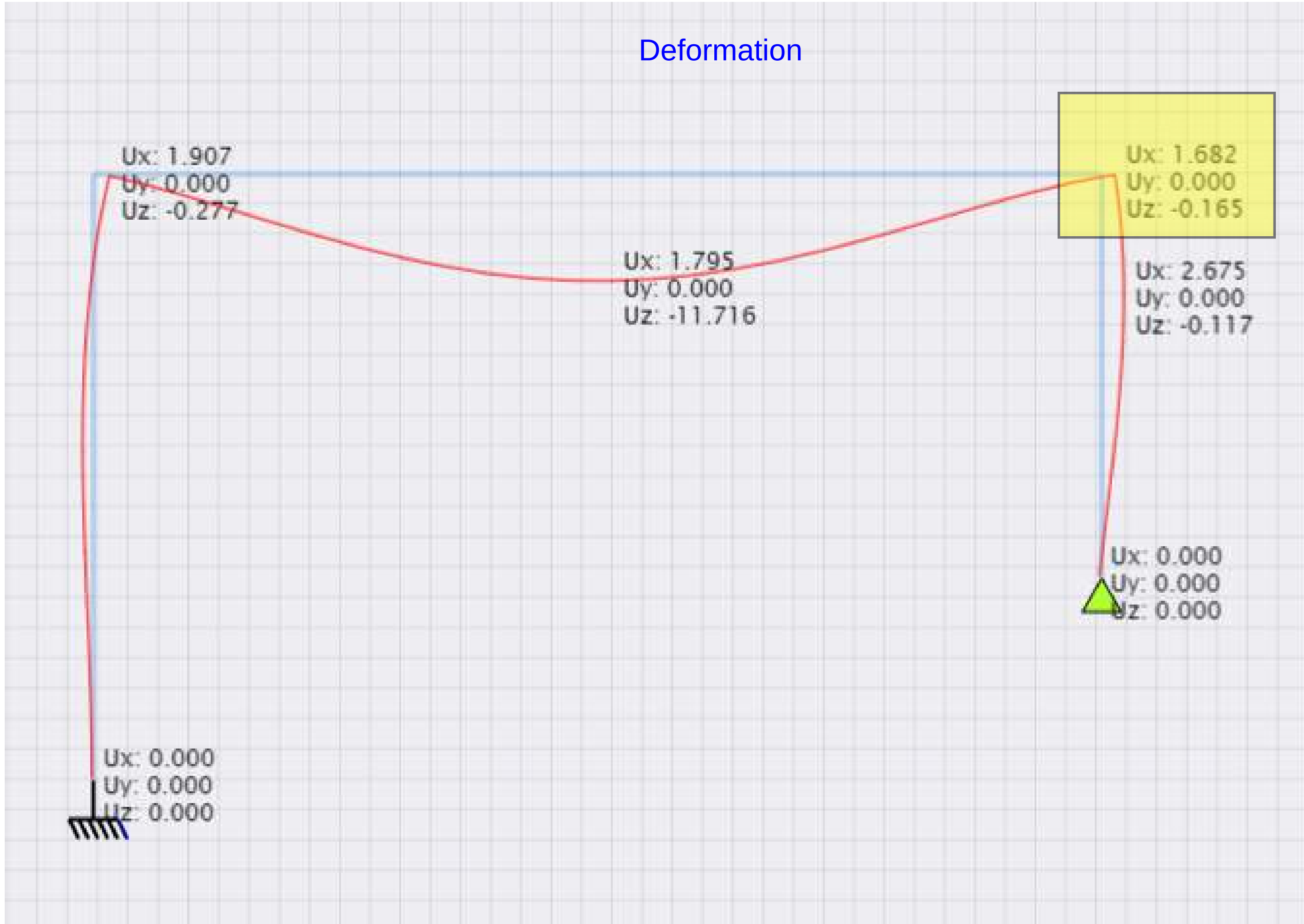
ETABS

Deformation



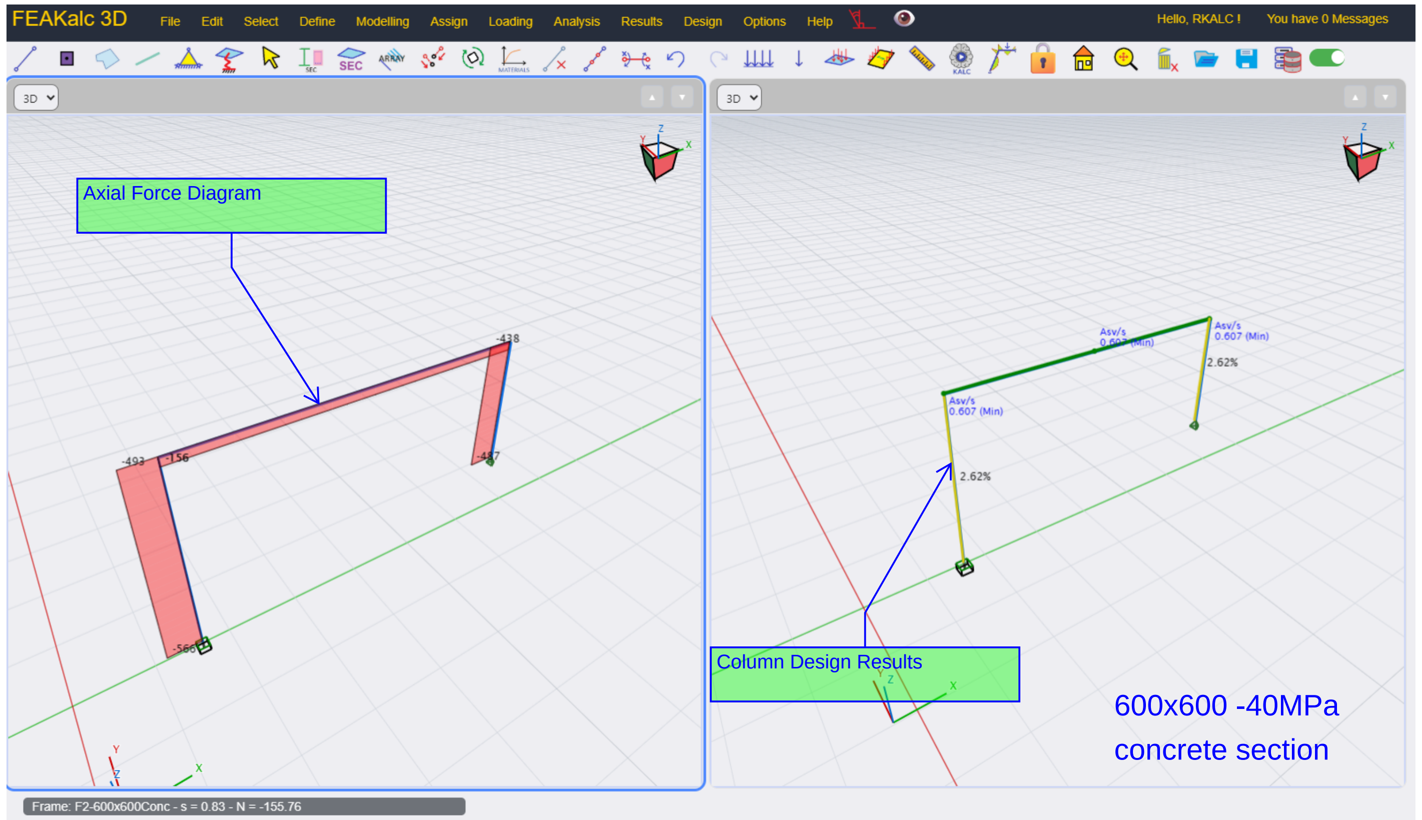
Load Combo : 1.2DL + 1.5LL

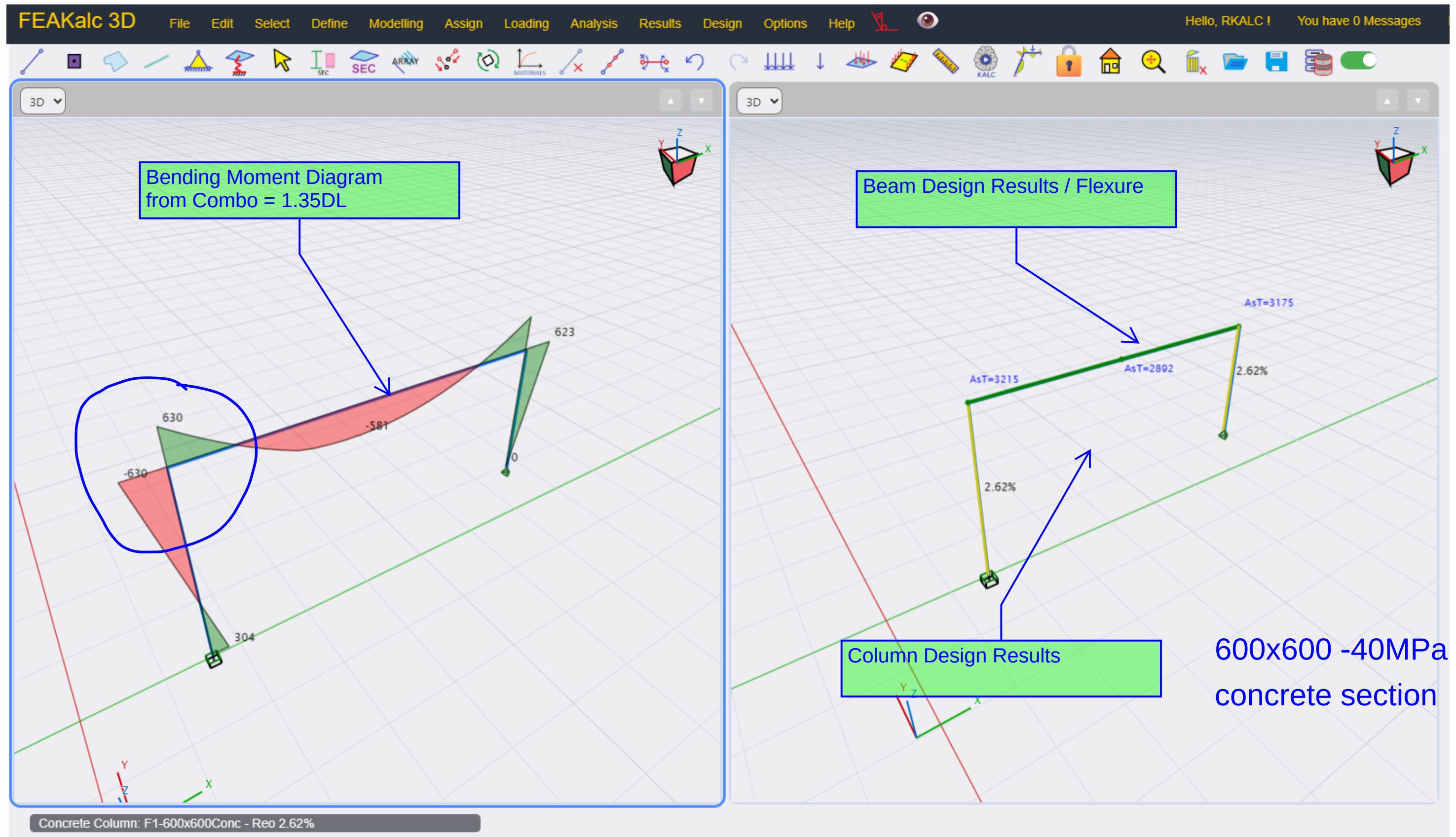
FEAKalc 3D

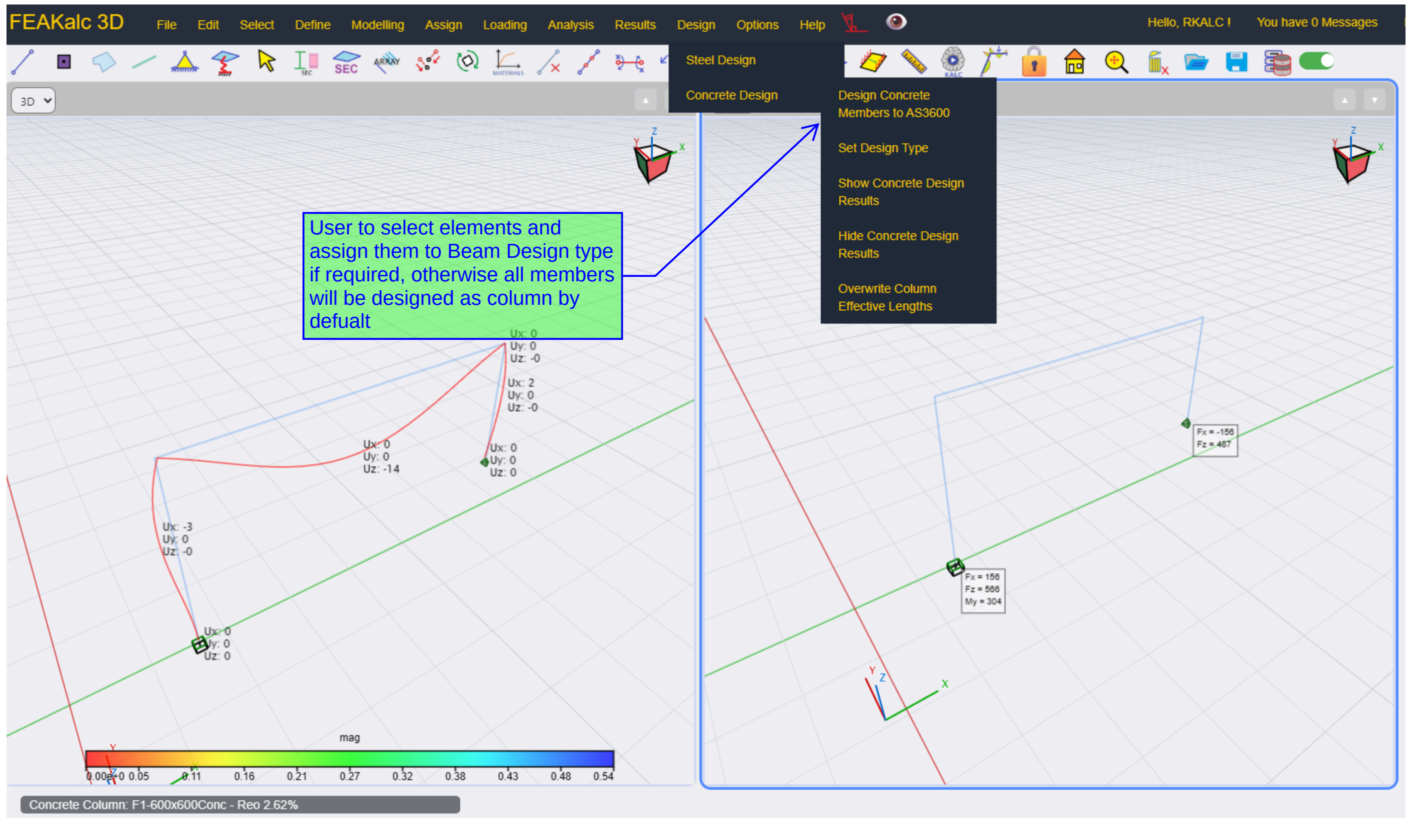


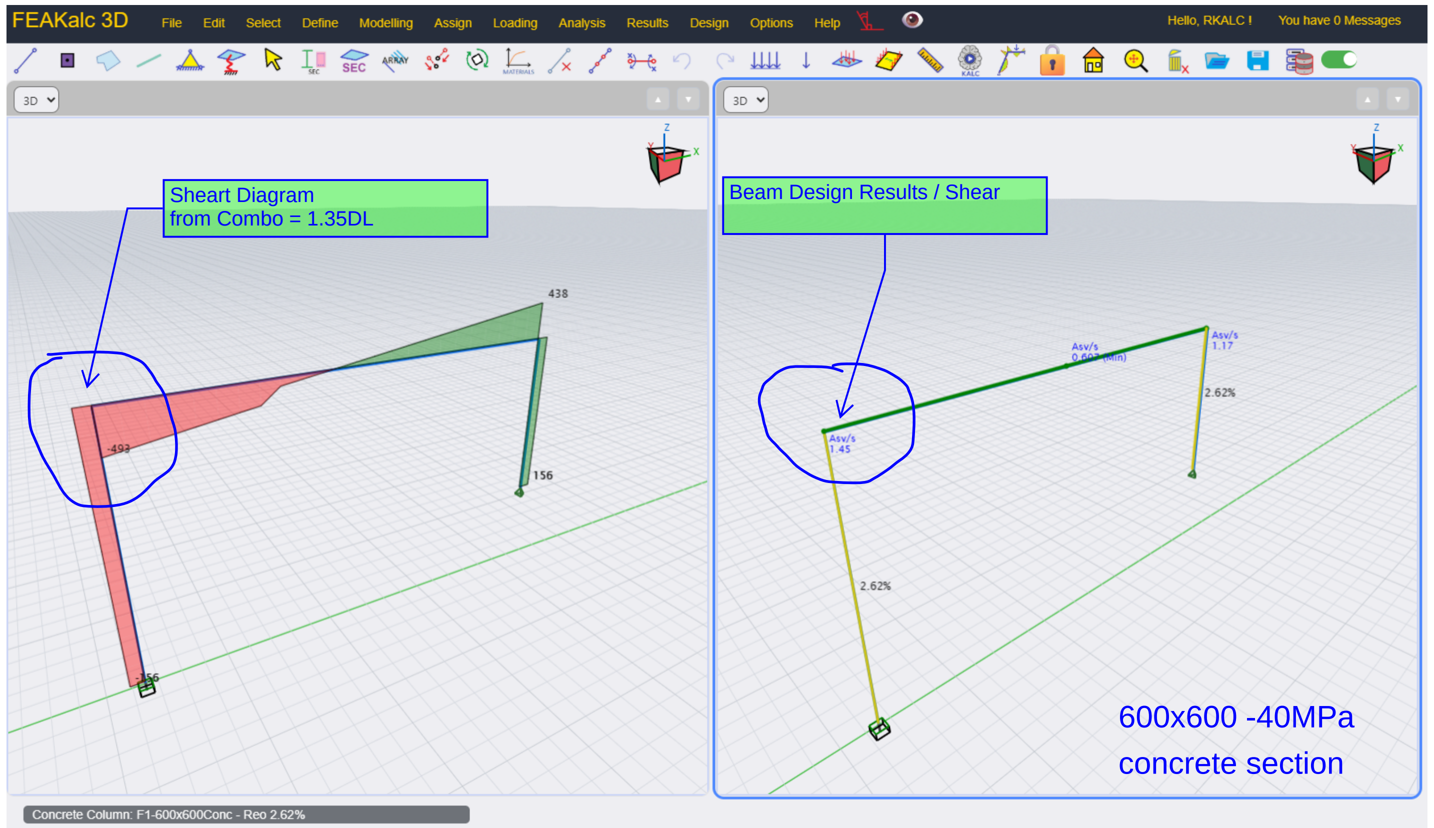
Load Combo : 1.2DL + 1.5LL

LEARNING CENTRE	Design to AS3600-2018	Concrete Frame	By: RK
RKALC		FEAKalc 3D Verifications	Sheet No.: 5
			Date: 7/26









Column Design Report

FEAKalc 3D Concrete Column Design Memo

AS 3600 RC Column Check

PASS

Member **F1**	Governing Load Case **LC-1.35DL**	Section **600 x 600**
f'c **40 MPa**	fy **500 MPa**	Cover to Reo Centre **54 mm**
Effective Length 22 **6000 mm**	Effective Length 33 **6000 mm**	Design Height **6000 mm**
Bars **7 x 10 N20**	Reinforcement **2.62 %**	Utilisation **85 %**

Governing

Design Height

Applied Design Actions

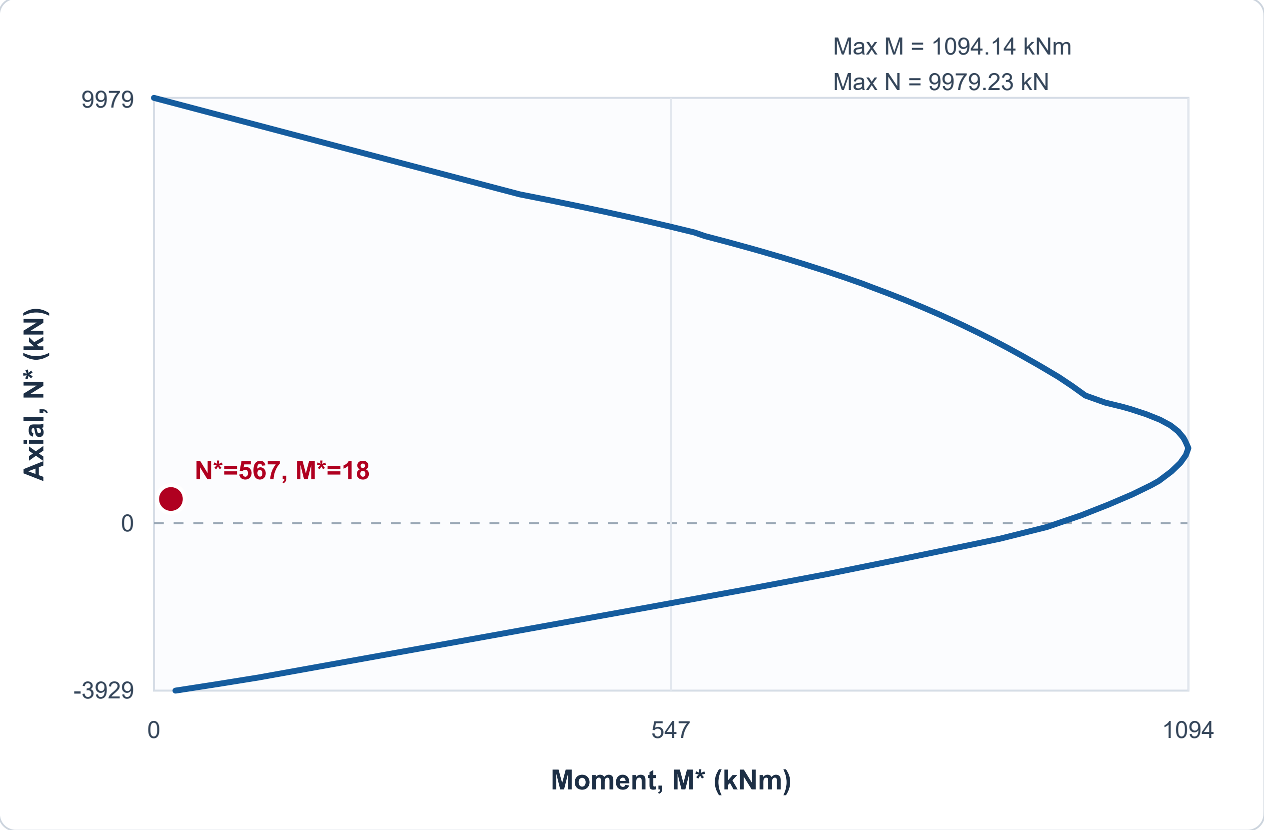
Item	Value
N*	567 kN
M22 top	16.99 kNm
M22 bottom	-16.99 kNm
M33 top	630.36 kNm
M33 bottom	-630.36 kNm

Design Height

Direction 22 Column Check

Item	Value
Balanced moment capacity	995 kNm
Euler buckling force, Ncr	14689 kN
Km	1.00
Moment magnifier, δb	1.04
Pure bending capacity	963.00 kNm
Design moment, M22*	18.00 kNm
N / bd index	1.58
M / bd² index	0.08
Utilisation	7.000000000000001%

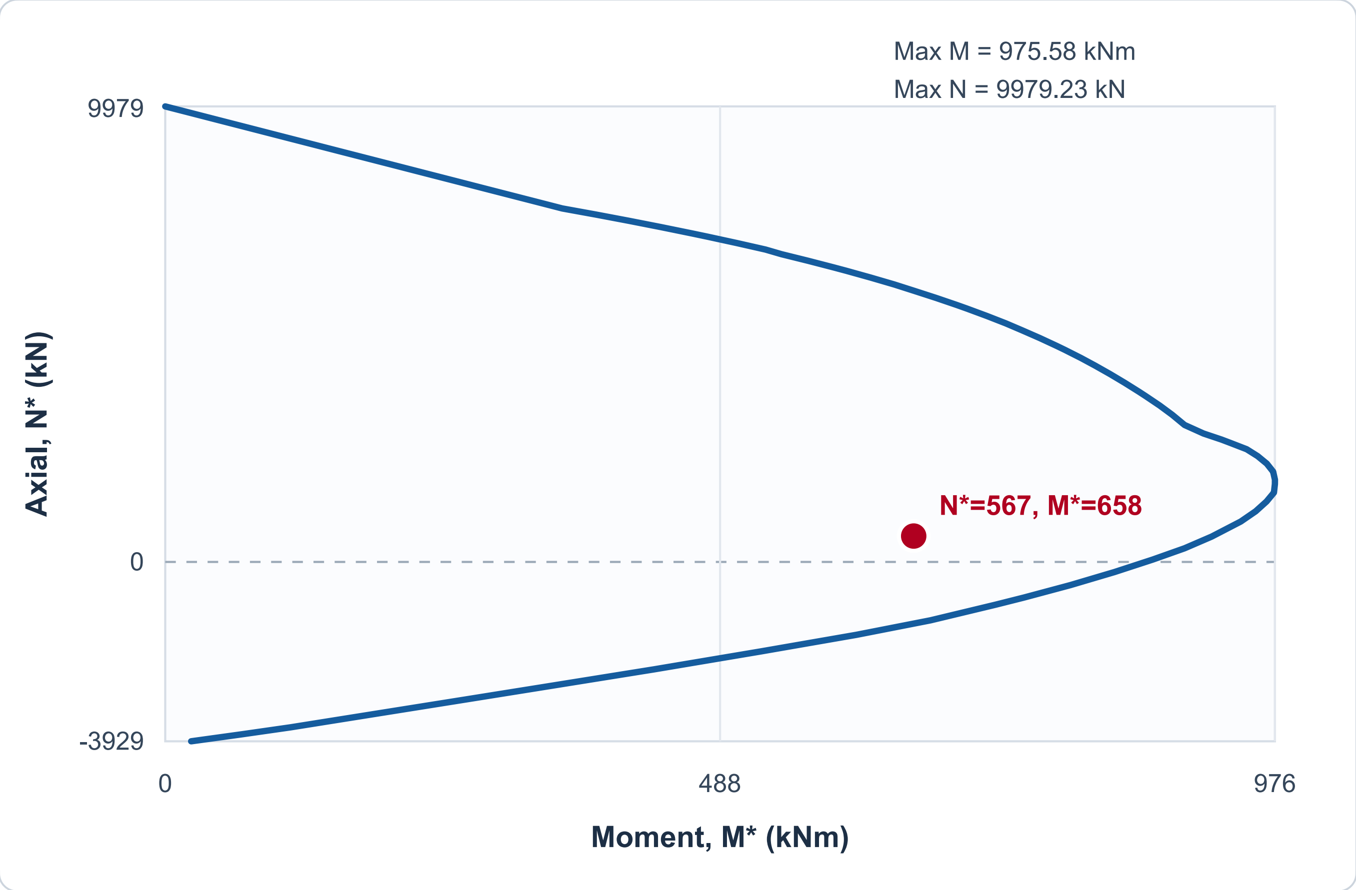
Interaction Diagram - Direction 22



Direction 33 Column Check

Item	Value
Balanced moment capacity	904.00 kNm
Euler buckling force, Ncr	13340 kN
Km	1.00
Moment magnifier, δb	1.04
Pure bending capacity	868.00 kNm
Design moment, M33*	658.00 kNm
N / bd index	1.58
M / bd² index	3.05
Utilisation	71%

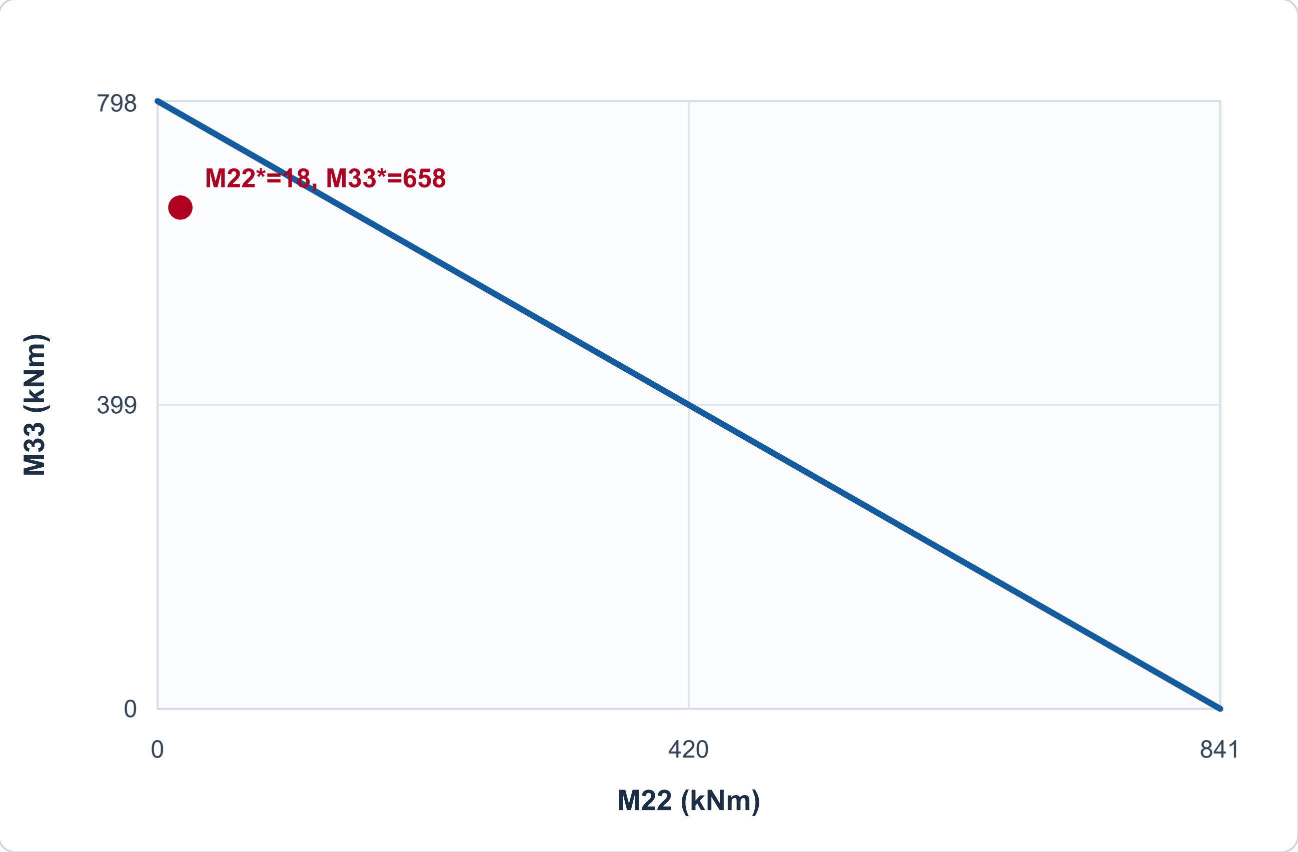
Interaction Diagrams- Direction 33



Axial and Biaxial Capacity

Item	Value
Squash load	9979 kN
Pure tension capacity	4006 kN
Muo 22	841.00 kNm
Muo 33	798.00 kNm
Biaxial power, αb	1.00
Biaxial utilisation	85%

Biaxial Interaction Diagram



Design Notes

Column reinforcement is selected from the concrete optimisation result.
The red marker represents the governing applied design action on each principal axis.

Following is a critical point cross check at corner (eave) of the frame where moment = 630 and co-existing shear = 493

Your Design Package is valid until 30/03/2030 10:44:38 PM

Inputs

Materials	
f'c (N/mm²)	40
fy (N/mm²)	500
fys (N/mm²)	500
Flexural Rebar Dia mm	N12
Shear Rebar Dia mm	N12
α=0.79 / γ=0.87	
Geometry (Units mm)	
Width	600
Depth	600
Bot. Cover to Centre	54
Top Cover to Centre	54
Torsion Cover (clear)	54
Loads (KN , m)	
Moment (ULS)	631
Moment (SLS)	1
M/bd²=3.53	
Shear - Coexisting	493
Torsion - Coexisting	Negligible
Axial force - for Shear (-ve for compression)	0

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NA d.=89 / Ku=0.1633 / Φ=0.85

Flexural Reo

As (mm²) - Required Bot.	2926
As - Adopted Bot **26N12**	2941
fs Mpa (tension Reo)	500
As' (mm²) - Required Top	Min
Adopted Top	as above
fs Mpa (comp Reo)	0
ΦMub (Max-Single)	1269
Flexural Capacity	634

Shear & Torsion

Veq (KN)	493
Shear Stress	1.67
Permitted Shear	8.1
ε =	0.001511
θv =	40
Kv=	0.122
ΦTcr (KN.m)	85
ΦVc (N/mm²)	0.58
Vs (N/mm²)	1.09
ΔFtd (KN)	402
Cl. 8.2.7 REO	946
Asw/S (mm²/mm)	0
Asv/S (mm²/mm)	1.44
Min Shear Legs	3
Required Spacing	236

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