KULTECH

UPPC v0.0 User's Manual

Nonlinear Cyclic Static Analysis of Unbonded Post-tensioned Precast Structures

January 2021

1. Introduction

KULTECH UPPC (Unbonded Post-tensioned Precast Concrete) v0.0 is a software that performs cyclic static moment-rotation analysis to capture the unique nonlinear behavior and energy dissipation parameters of UPPC systems.

UPPC systems cannot be modeled with conventional techniques because of the following reasons:

- Lateral load resisting system consists of precast members connected by post-tensioning strands which are unbonded throughout their entire length. These strands are an essential part of lateral load capacity and their strain-stress levels should be calculated accurately. This requires special modelling techniques which should take into account the kinematic and static equilibrium of the strands in a global sense.
- The unbonded nature of the strands also cause 'strain compatibility' phenomenon to be non-applicable, therefore special formulations should be implemented to establish force equilibrium in section analysis.
- Due to the lack of damage mechanisms (yielding of mild steel, plastic hinging and cracking of concrete) which are assumed for the 5% damping ratio considered for conventional reinforced concrete structures, equivalent viscous damping ratios for UPPC systems can be overestimated if the 5% value is used in spectral analysis.
- The performance criteria set for conventional systems like yielding of steel are irrelevant for UPPC systems and special performance criteria should be defined for them.

For detailed information about this unique behavior of UPPC systems, please refer to Appendix A of this document.

El Sheikh et al [3] pointed out that defining a zero-length link element with the calculated moment-rotation behavior at beam-column joint yields reasonably close results to detailed fiber element model. Therefore, a practical way to incorporate the unique behavior of UPPC systems to global structural computer models is to define moment-rotation relations at the relevant beam-column joints. This phenomenon is illustrated in Figure 1 on a simple frame. Figure 1.1 shows an outline of the frame, Figure 1.2 shows the tools that should be used in the global model to capture the behavior, Figure 1.3 shows the simplified zero-link joint member model. In addition to the aforementioned simplified modelling method, equivalent viscous damping ratios calculated from the cyclic hystereses can be used to scale the response spectrum used for earthquake analysis.

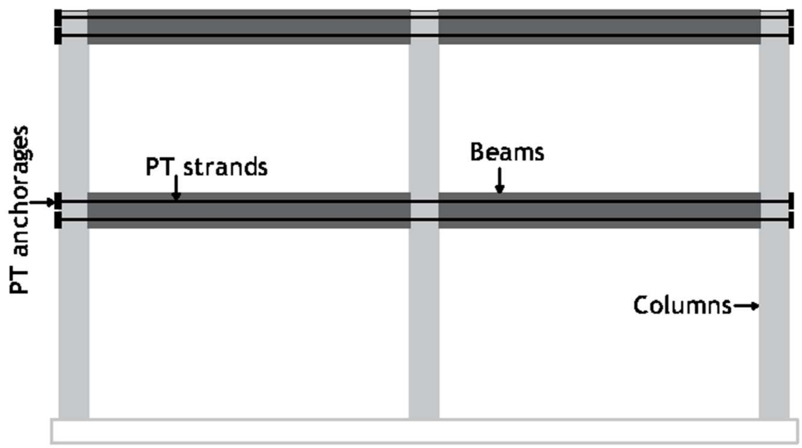


Figure 1.1 - Outline of the sample frame

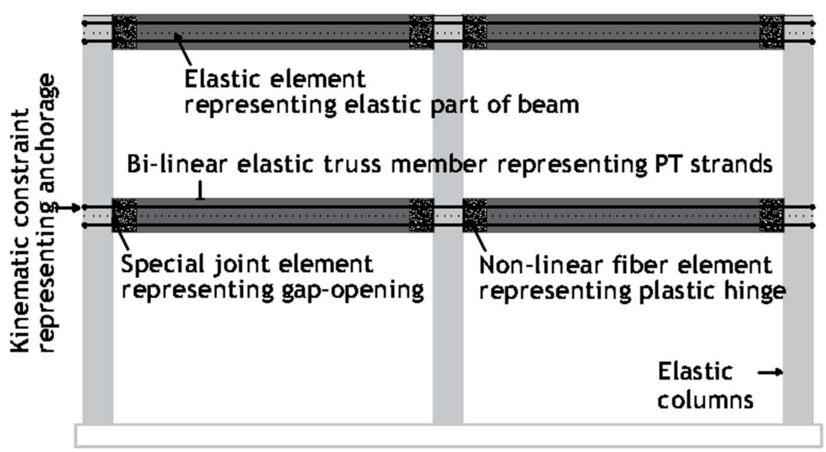


Figure 1.2 - Fiber element model

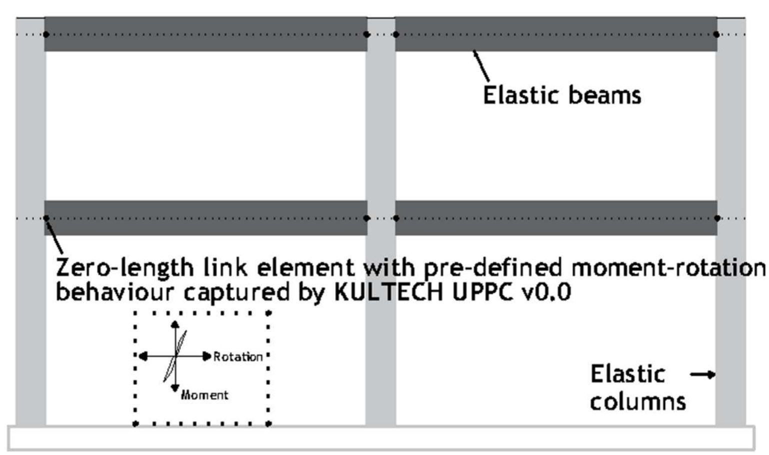


Figure 1.3 - Simplified zero-length link model with KULTECH UPPC v0.0

KULTECH UPPC v0.0 works on the sub-assembly level. The sub-assembly consists of the beam which is 'cut' from its mid-span (which is assumed to be the contra-flexure point under lateral loading) and the column. This sub-assembly then is turned 90 degrees and a lateral cyclic displacement history is applied to the beam end to determine the moment-rotation behavior at beam-column joint. Note that in the sub-assembly, the horizontal stub member which represents the column is a fixed member. Since columns in UPPC systems are assumed to behave elastically, this is considered to have negligible effect on the moment-rotation behavior of the sub-assembly. However, the column size should be incorporated in the sub-assembly correctly to accurately calculate unbonded length of the strands.

The sub-assembly logic of KULTECH UPPC v0.0 will be illustrated using the simple frame shown in Figure 1. To get the moment-rotation relation that will be defined in the zero-length link at the joint between the first storey left beam and the left column, the sub-assembly that will be taken is shown in Figure 2. Members of the sub-assembly and the displacement protocol is shown in Figure 3.

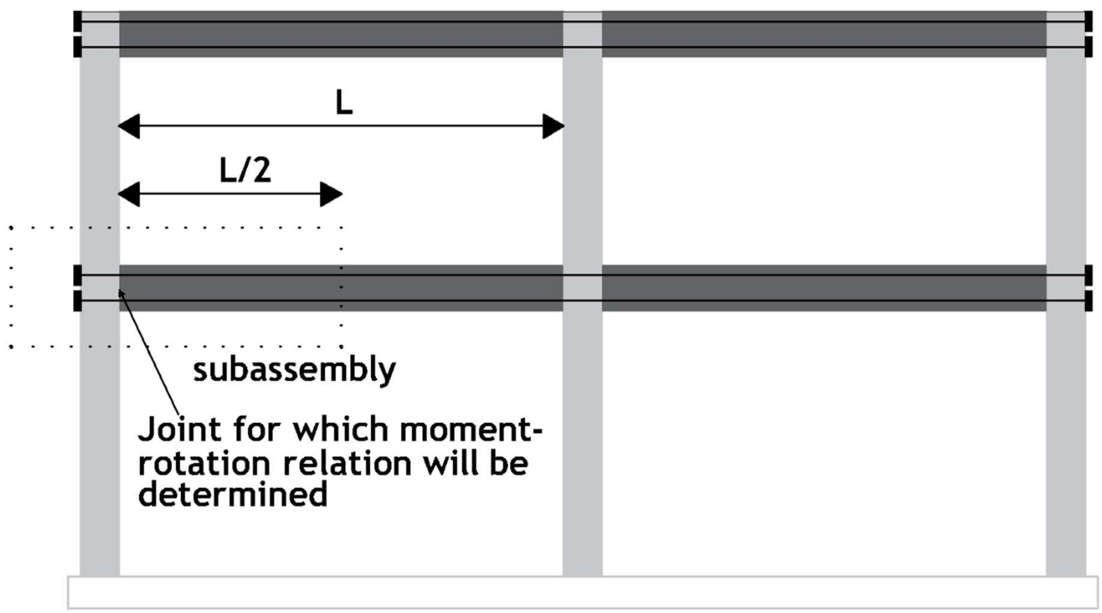


Figure 2 - Sub-assembly shown on sample frame

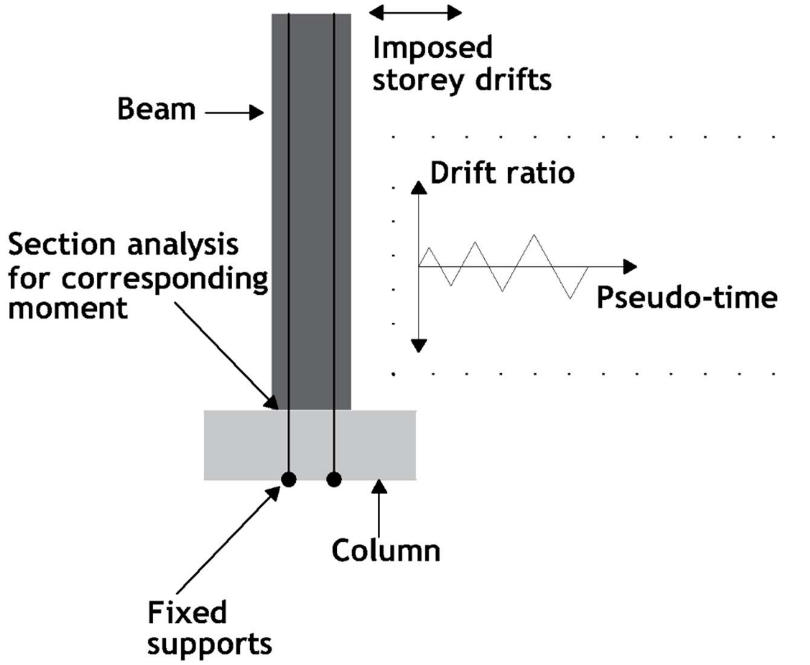


Figure 3 - Sub-assembly parameters

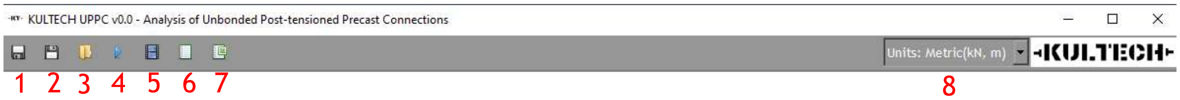
In KULTECH UPPC v0.0, user defines the geometric parameters of the sub-assembly, material properties of all the materials that will be used, the desired displacement history in terms of drift ratio and the fiber concrete section properties. The program then performs and presents the following analyses:

- Cyclic nonlinear moment-rotation behavior (hysteresis) of the beam-column joint taking into account nonlinear behavior of unconfined and confined concrete and post-tensioning strands
- Graphical and numerical presentation of all performance points to be used in Performance-Based Seismic Analysis
- Separate hysteresis results for all defined storey drift ratios
- Relative energy dissipation ratio β and equivalent viscous damping ratio ξ_{eq} for all defined drift ratios
- Concrete section strains, stresses and forces for any desired stage in the analysis
- Concrete strain-stress history for any desired fiber of the beam section
- Strain-stress history of post-tensioning strands
- A tabelized version of all the results for all the stages
- A 3-D simulation that illustrates the deformation/displacement and also performance points of the sub-assembly

Following section describes in detail the User Interface of KULTECH UPPC v0.0.

2. User Interface

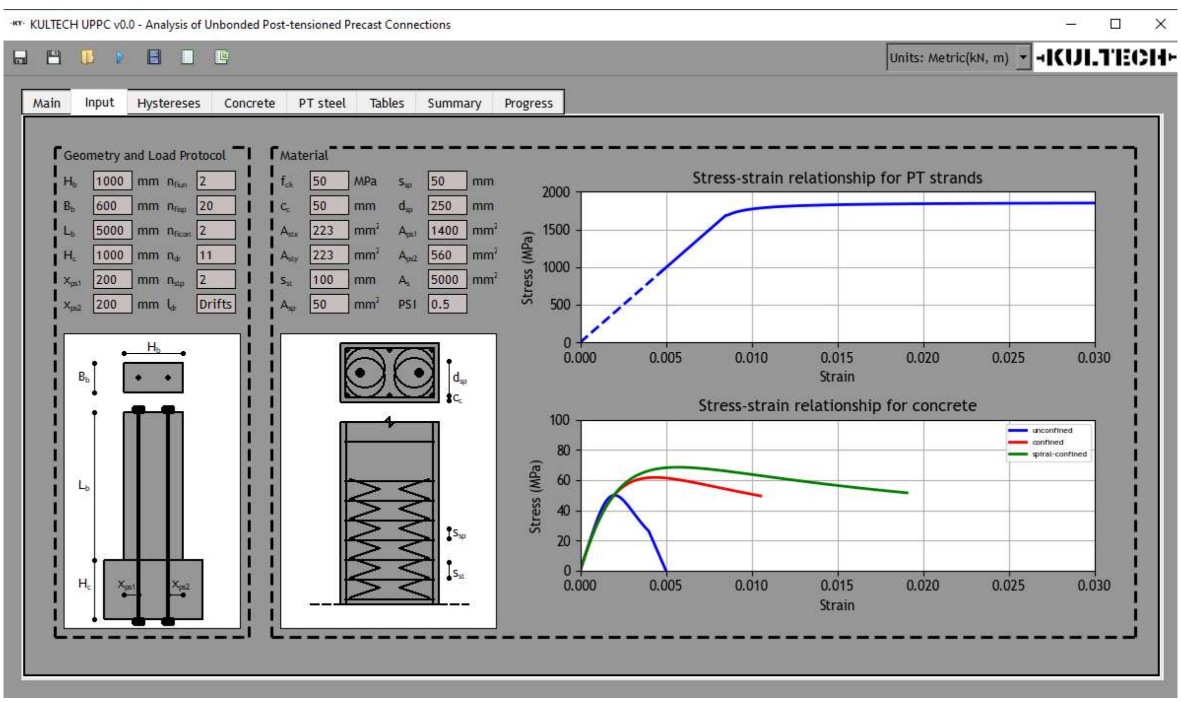
Toolbar

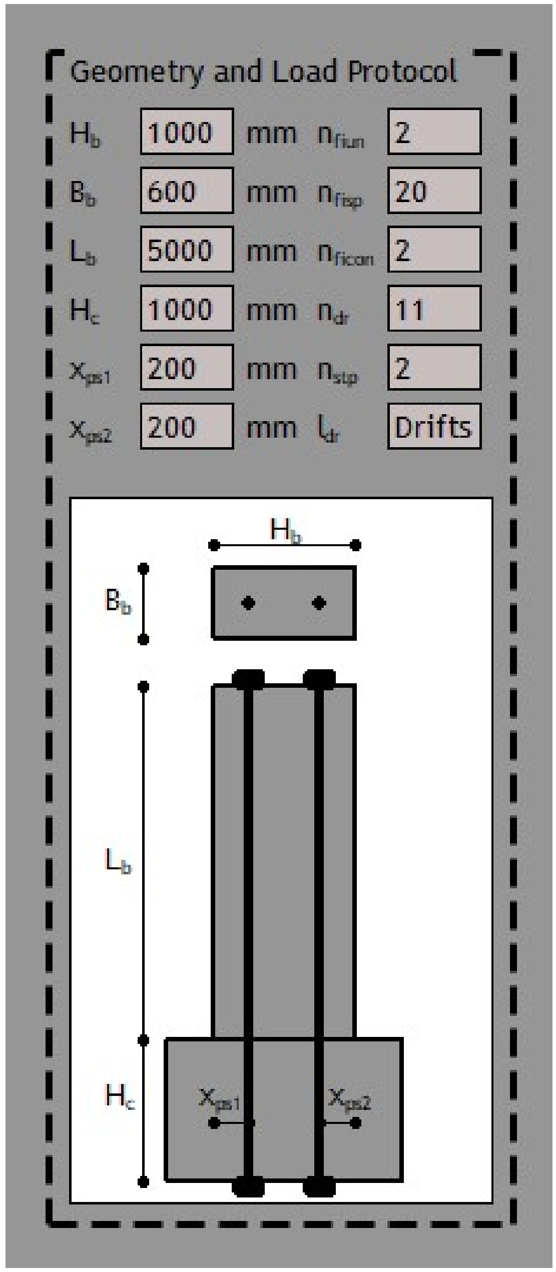


The toolbar consists of 7 actions and a combo box from which the user can choose metric units or US units.

1: Save the analysis file to existing
2: Save the analysis file to another file
3: Open an existing analysis file
4: Start analysis
5: Start simulation (If analysis has already been performed)
6: Open User's Manual
7: Export results to MS Excel (If analysis has already been performed)
7: Change units. Available units are Metric and US.

Input Tab





Geometry and Load Protocol

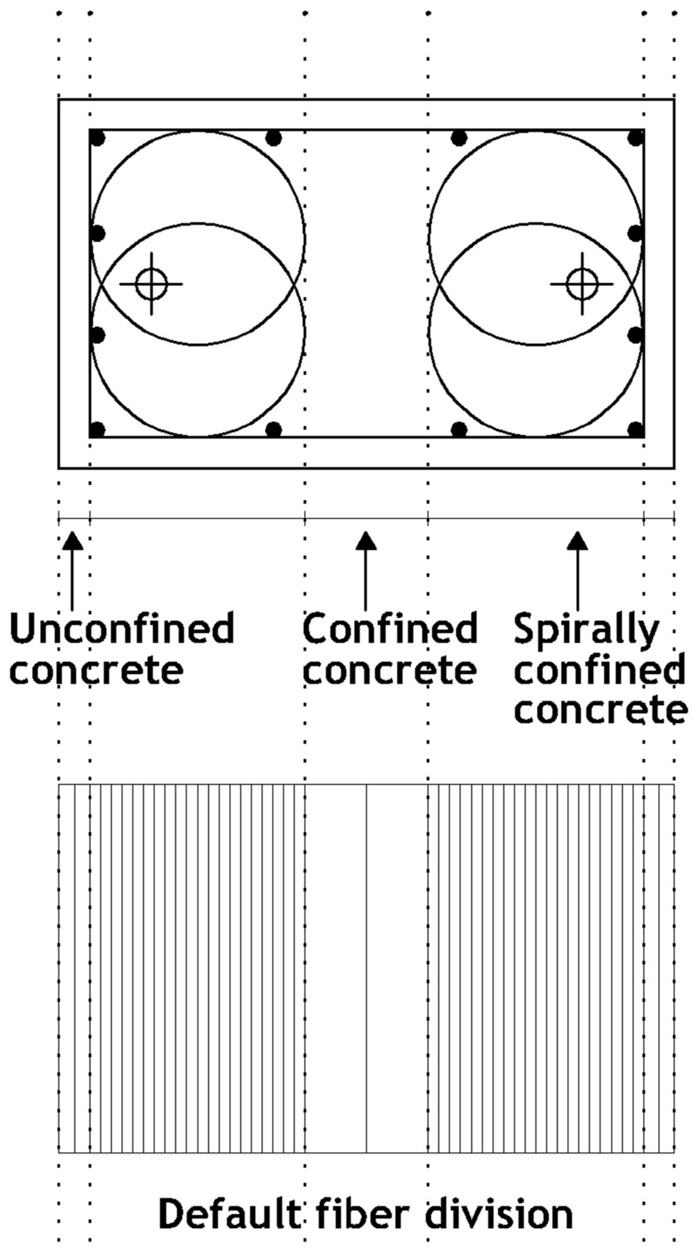
This part is where the user enters input for the geometry of the sub-assembly, the section fibers and the load protocol to be applied.

The geometry part is self-explanatory with the figure on the interface. Section fiber and load protocol input will be explained in further detail.

KULTECH UPPC conducts sectional analysis by dividing the beam section into fibers. The section itself is divided into three parts, unconfined concrete, spirally confined concrete and confined concrete.

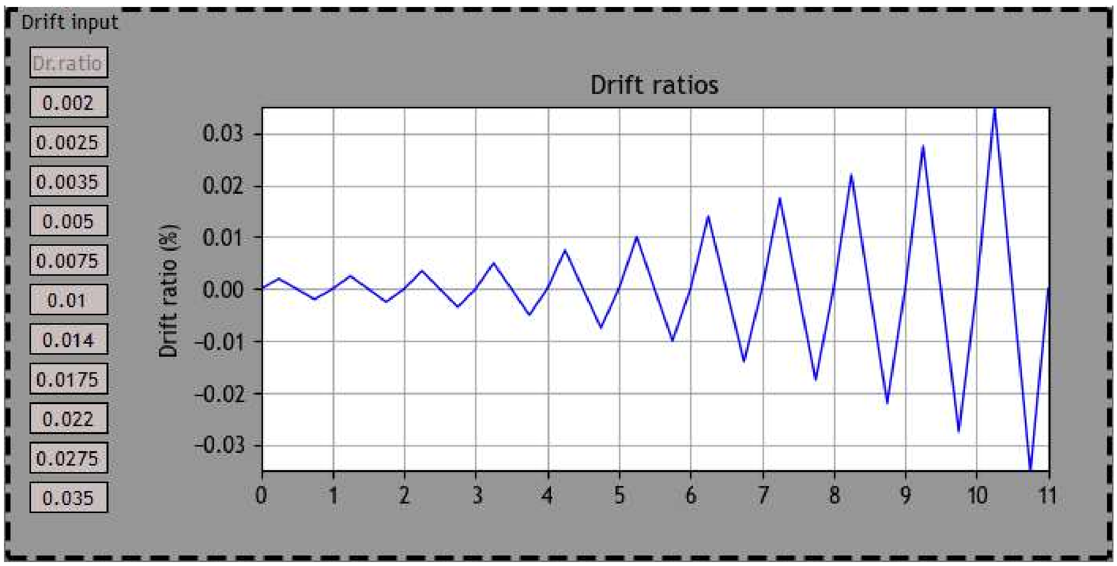
n_{fiun} = Number of fibers unconfined concrete will be divided into
n_{fisp} = Number of fibers spirally confined concrete will be divided into
n_{ficon} = Number of fibers confined concrete will be divided into

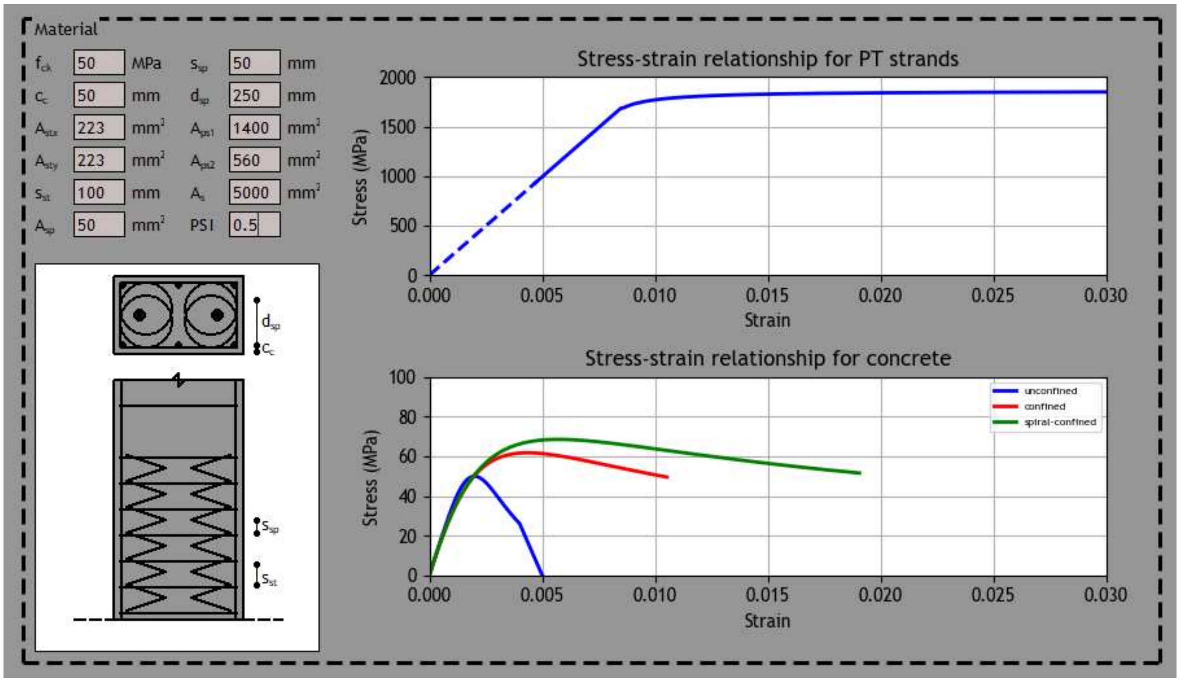
Default values for n_{fiun}, n_{fisp} and n_{ficon} are 2, 20 and 2, respectively. It is recommended these default values are used for optimum performance. However, if convergence issues arise or if it is desired to capture concrete behavior in particular fibers, they can be changed.



The cyclic displacement protocol in terms of drift ratio is defined using the following input parameters:

n_{dr} = Number of drift ratios the sub-assembly will be subjected to. This value can be maximum 11.
n_{stp} = Number of steps to the drift ratio. This value is by default set to 2 for performance optimization. However, in case convergence issues arise, it can be increased.
l_{dr} = List of drift ratios (in percentage) to be applied to the subassembly. When you click on the 'Drifts' button next to l_{dr} input, the following window opens to enter drift ratio values.





Material

Material parameters for concrete and post-tensioning strands are defined using the input table as follows:

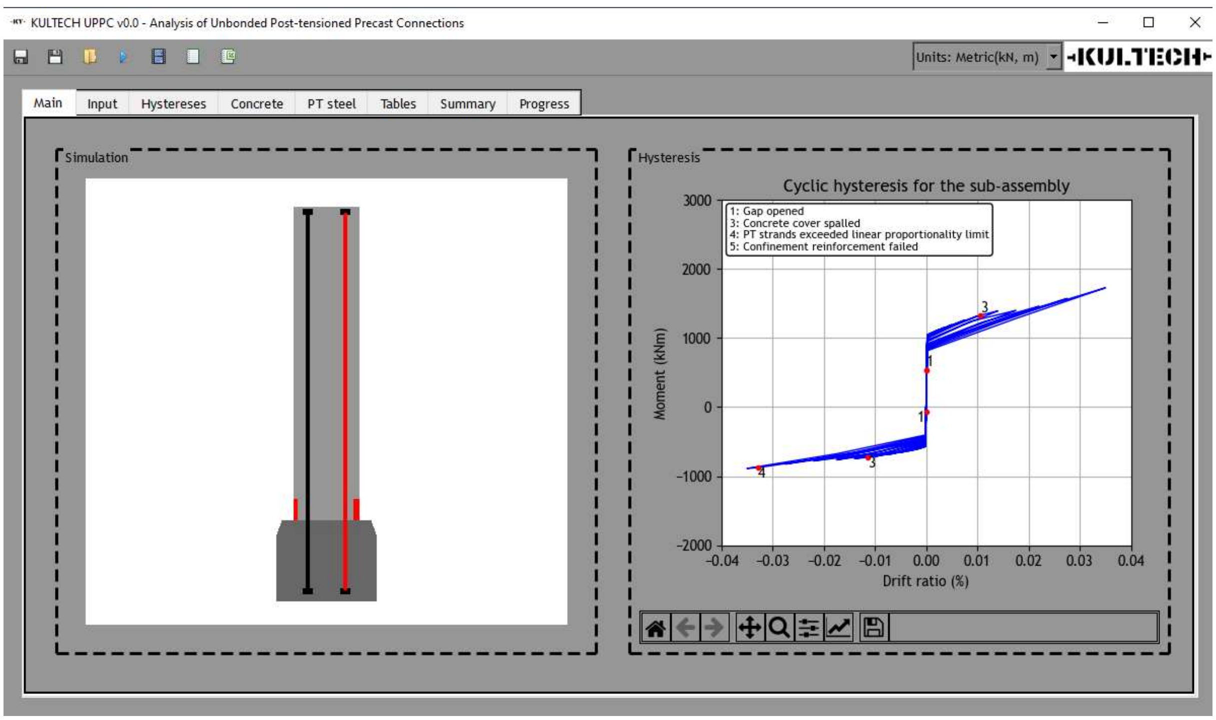
f_{ck} = Characteristic compressive strength of concrete
c_c = Clear cover to axis of stirrups
A_{stx} = Total cross-sectional area of stirrups in X-direction
A_{sty} = Total cross-sectional area of stirrups in Y-direction
s_{st} = Longitudinal spacing distance of stirrups
A_{sp} = Cross-sectional area of spiral reinforcement
s_{sp} = Longitudinal spacing distance of spiral reinforcement
d_{sp} = Diameter of spiral reinforcement
A_{ps1} = Total cross-sectional area of left layer of post-tensioning strands
A_{ps2} = Total cross-sectional area of right layer of post-tensioning strands
A_{st} = Total cross-sectional area of longitudinal mild reinforcement
PSI = Ratio of initial jacking stress of PT strands to ultimate strength

Once all relevant input boxes are filled, the stress-strain plots of PT strands and concrete (unconfined, spirally confined and confined) are presented automatically.

Main Tab

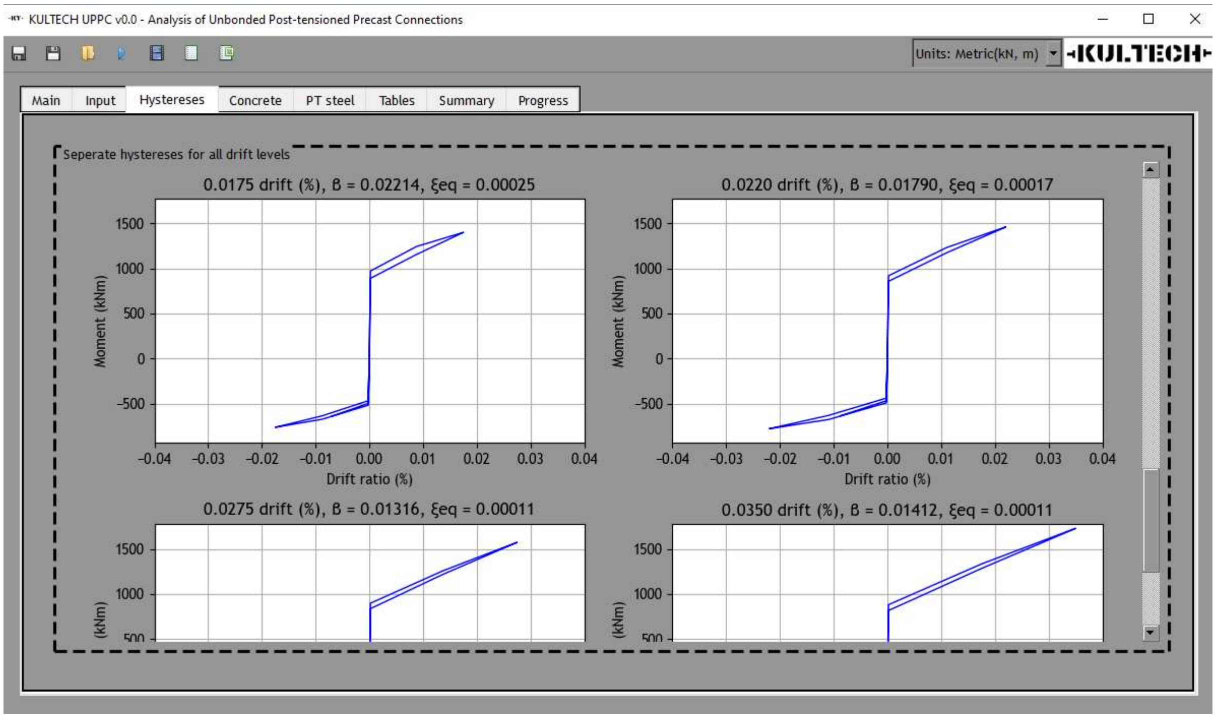
After input is defined and analysis is started, the hysteresis plot on the right side of the main tab presents a live demonstration of the moment-rotation curve of the subassembly as the analysis proceeds. (An alternative way to follow the analysis is the Progress Tab, which will be described later)

The performance points described at Appendix A is also displayed on the plot. After the analysis ends, the Simulation button can be clicked to show a re-drawing of the moment-rotation plot. Synchronized with it, the Simulation box on the left side shows a scaled simulation the subassembly's displacement. Also, when certain performance limits are exceeded, relevant members of the subassembly are colored in red. (For example, when PT strands reach the limit of linear proportionality, they are colored in red)



Hystereses Tab

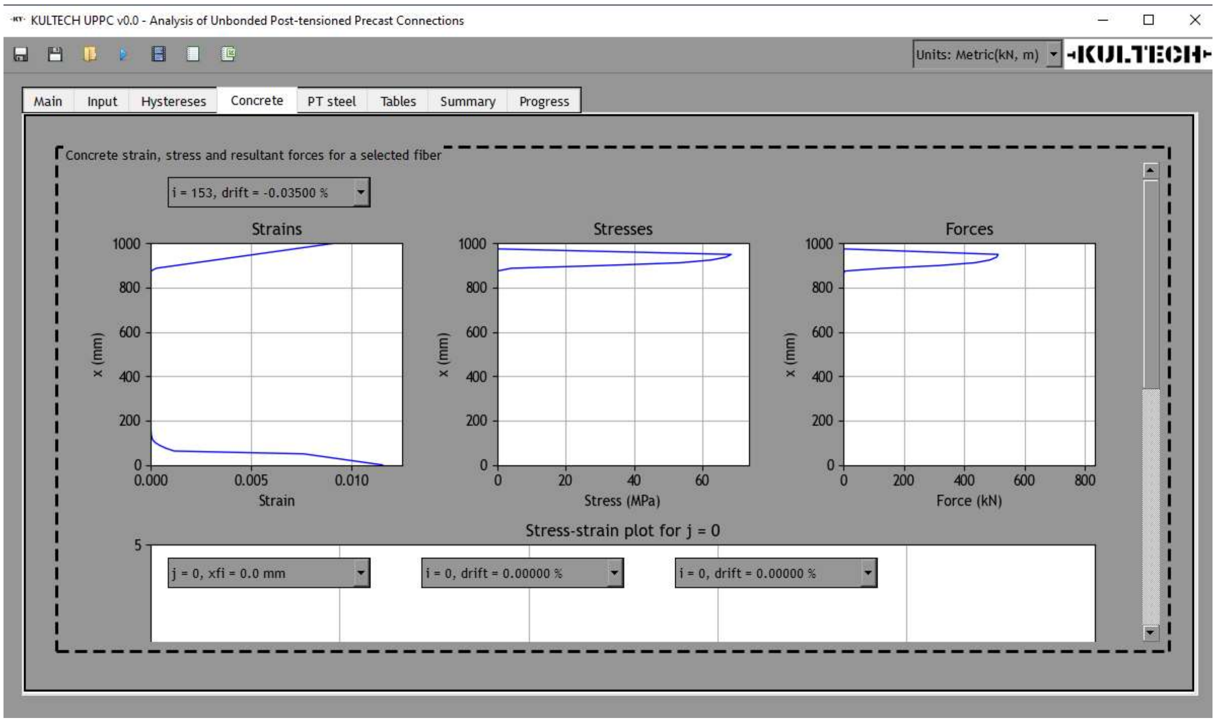
In the Hystereses Tab, the user can see the drift protocol applied to the top of the beam and separate moment-rotation plots for all drifts, along with the corresponding energy dissipation parameters, relative energy dissipation ratio ß and equivalent viscous damping ratio ξeq.



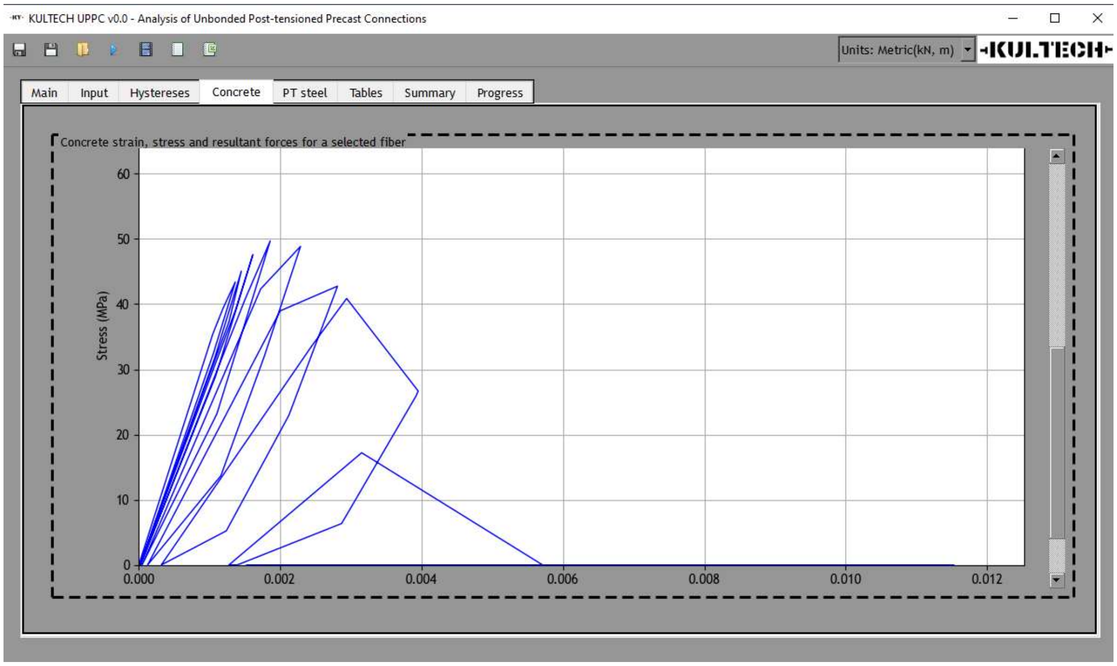
Concrete Tab

Concrete Tab displays to the user the state of concrete (strains, stresses and forces) at any given fiber section at any given stage in the analysis.

The top part with 3 plots horizontally laid out shows the strains, stresses and resultant forces along the beam section at the selected stage of analysis.

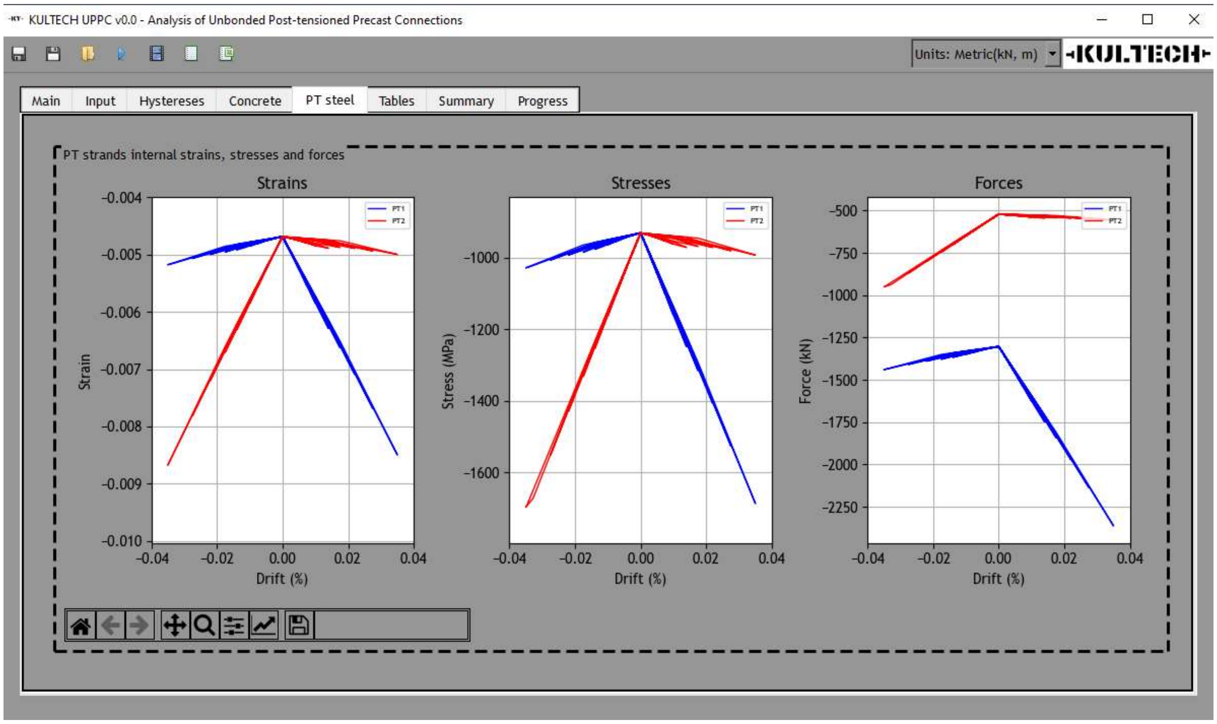


The plot at the bottom part shows the stress-strain history of the selected fiber between the chosen analysis stages.



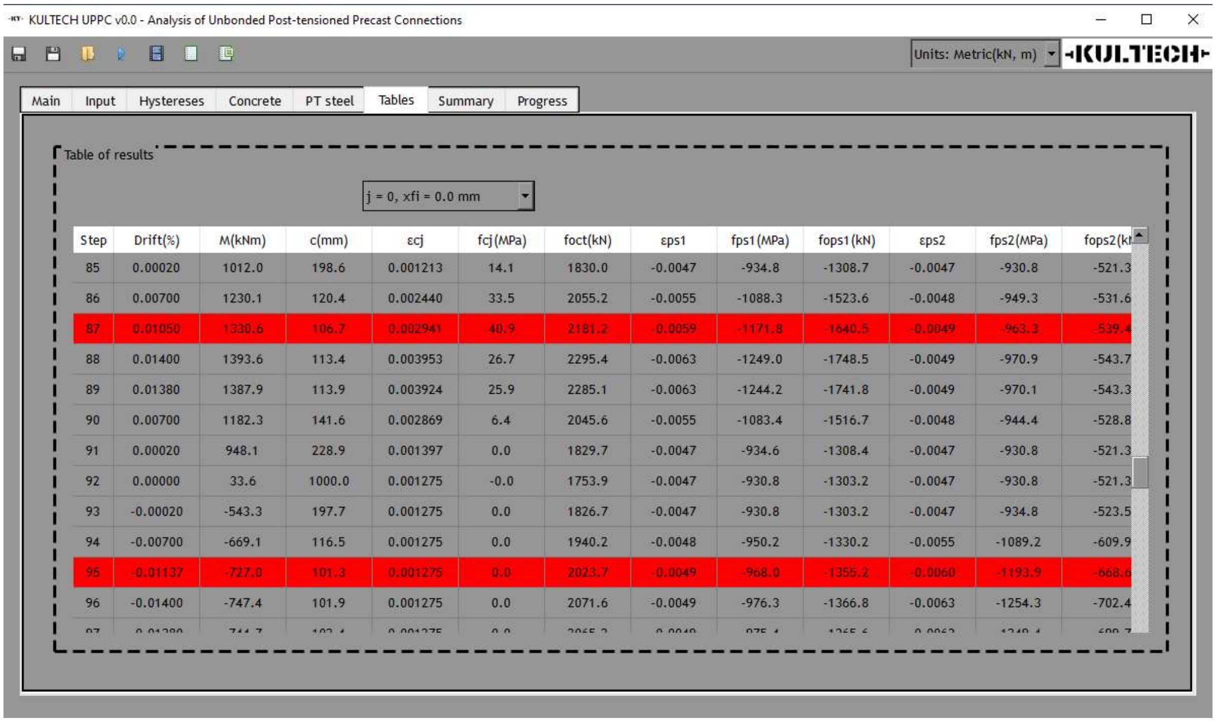
PT Steel Tab

In this tab, the strain, stress and force histories of both post-tensioning tendons are presented.



Tables Tab

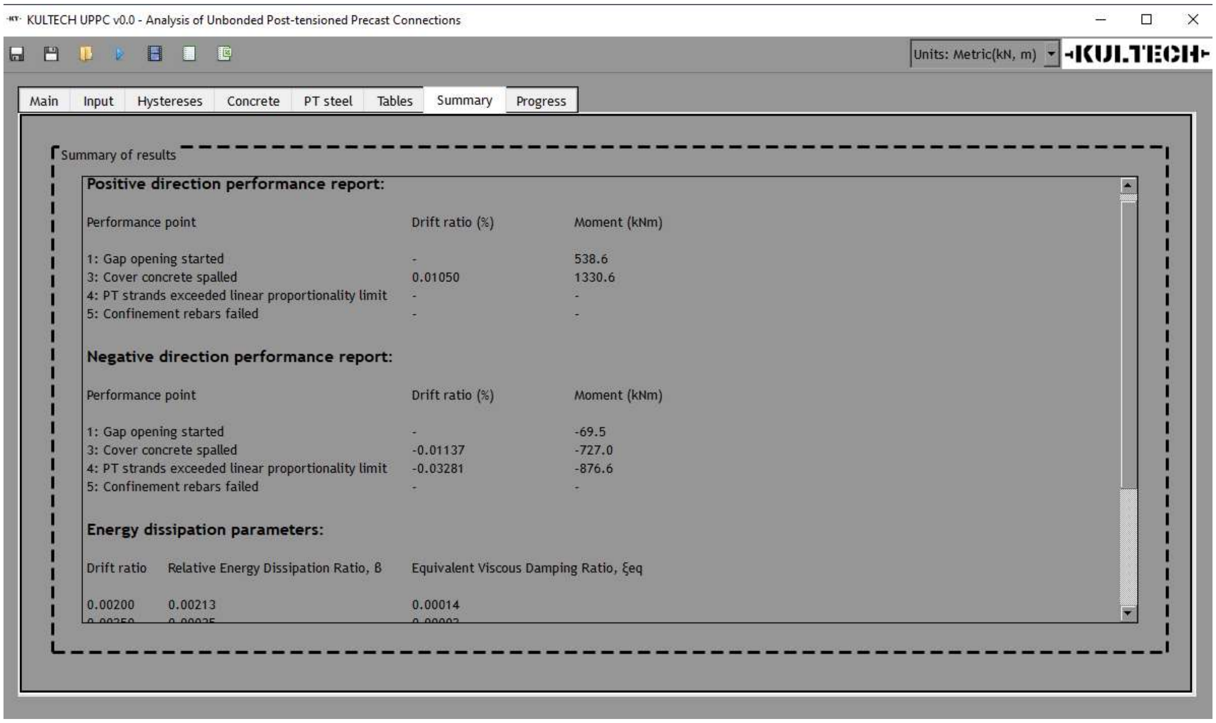
Tables Tab displays all the results in table format. The user can choose the desired concrete fiber for which results are needed from the combobox at the top. The stages at which the performance limits are exceeded are also highlighted with red.



Step	Drift(%)	M(kNm)	c(mm)	εcj	fcj(MPa)	foct(kN)	εps1	fps1(MPa)	fops1(kN)	εps2	fps2(MPa)	fops2(kN
85	0.00020	1012.0	198.6	0.001213	14.1	1830.0	-0.0047	-934.8	-1308.7	-0.0047	-930.8	-521.3
86	0.00700	1230.1	120.4	0.002440	33.5	2055.2	-0.0055	-1088.3	-1523.6	-0.0048	-949.3	-531.6
87	0.01050	1330.6	106.7	0.002941	40.9	2181.2	-0.0059	-1171.8	-1640.5	-0.0049	-963.3	-539.4
88	0.01400	1393.6	113.4	0.003953	26.7	2295.4	-0.0063	-1249.0	-1748.5	-0.0049	-970.9	-543.7
89	0.01380	1387.9	113.9	0.003924	25.9	2285.1	-0.0063	-1244.2	-1741.8	-0.0049	-970.1	-543.3
90	0.00700	1182.3	141.6	0.002869	6.4	2045.6	-0.0055	-1083.4	-1516.7	-0.0048	-944.4	-528.8
91	0.00020	948.1	228.9	0.001397	0.0	1829.7	-0.0047	-934.6	-1308.4	-0.0047	-930.8	-521.3
92	0.00000	33.6	1000.0	0.001275	-0.0	1753.9	-0.0047	-930.8	-1303.2	-0.0047	-930.8	-521.3
93	-0.00020	-543.3	197.7	0.001275	0.0	1826.7	-0.0047	-930.8	-1303.2	-0.0047	-934.8	-523.5
94	-0.00700	-669.1	116.5	0.001275	0.0	1940.2	-0.0048	-950.2	-1330.2	-0.0055	-1089.2	-609.9
95	-0.01137	-727.0	101.3	0.001275	0.0	2023.7	-0.0049	-968.0	-1355.2	-0.0060	-1193.9	-668.6
96	-0.01400	-747.4	101.9	0.001275	0.0	2071.6	-0.0049	-976.3	-1366.8	-0.0063	-1254.3	-702.4

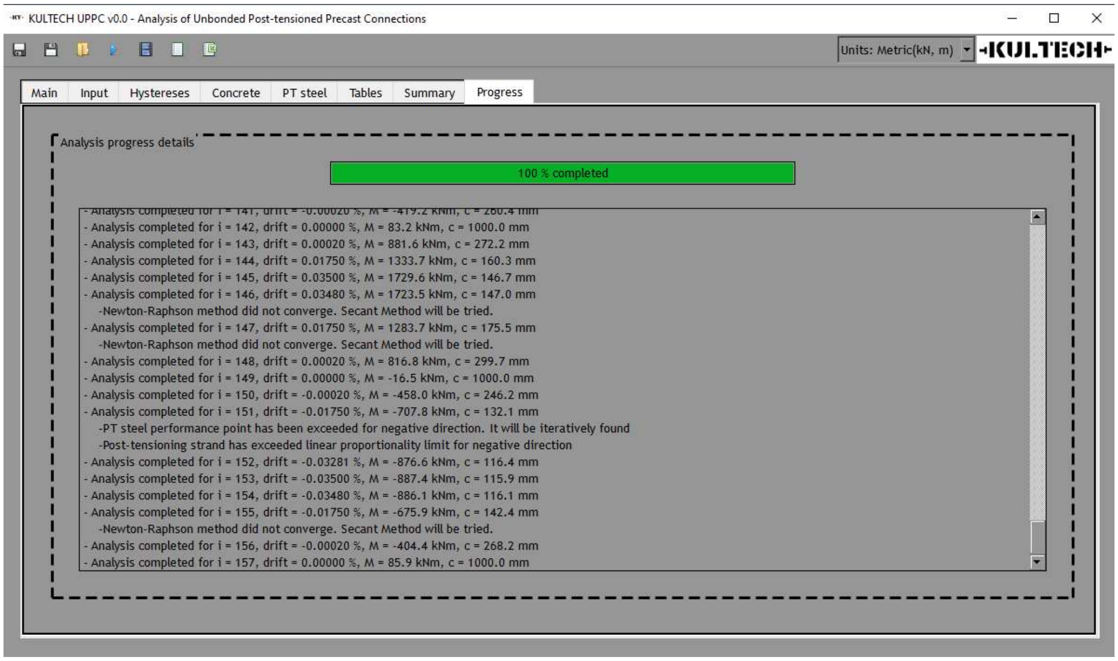
Summary Tab

Summary Tab presents the summary of the results in terms of performance points and energy dissipation parameters of the subassembly.



Progress Tab

The user can follow the progress of the analysis from the Progress Tab.



3. Example

The frame shown in Figure 3.1 is used to illustrate an example of how to use KULTECH UPPC. It is assumed that preliminary gravitational and lateral load analyses have been performed to determine approximate beam dimensions and strand areas. In order not to deviate from the scope of KULTECH UPPC, steps of this preliminary analysis are not shown. The right beam-column joint at the 4th floor (drawn in subassembly box in the figure) is analyzed.

Please note that preliminary analysis which is used to determine approximate dimensions and strand areas do not necessarily require the unique modeling techniques mentioned in this document. However, these modeling techniques are necessary to finalize the analysis and design of such systems.

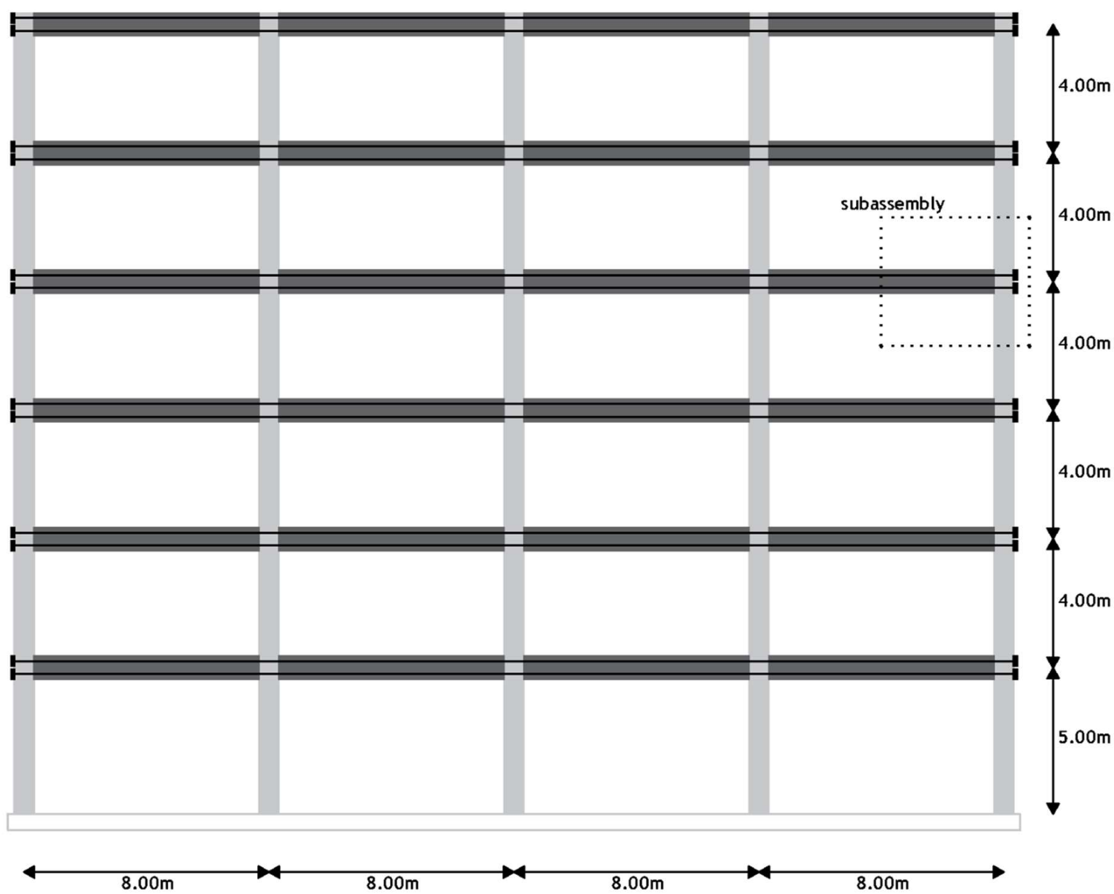
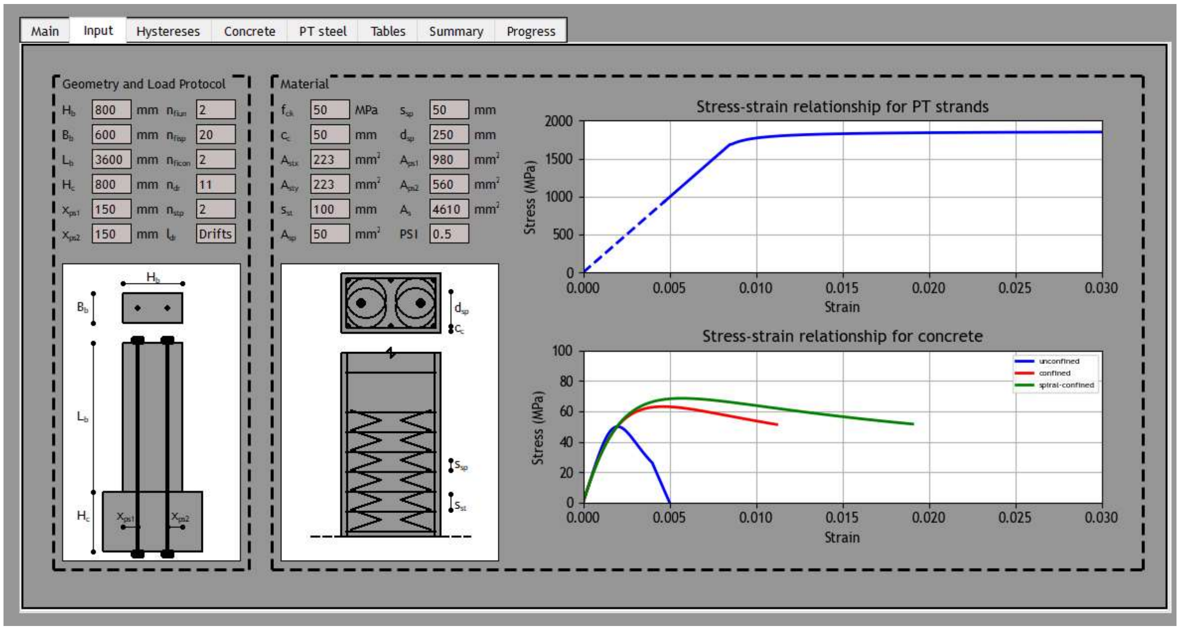


Figure 3.1 – Example frame dimensions

Results obtained from preliminary analysis of the frame for the joint that will be analyzed are given below:

Parameter	Value
Positive design moment due to relevant combination of lateral and gravitational loads, M_{DEQ}^{+}	230 kNm
Negative design moment due to relevant combination of lateral and gravitational loads, M_{DEQ}^{-}	770 kNm
Negative design moment due to relevant combination of gravitational loads only, M_{DGR}^{-}	270 kNm
Height of beam, H_b	800 mm
Width of beam, B_b	600 mm
Height of column, H_c	800 mm
Total cross-sectional area of post-tensioning strands at top of beam, A_{ps1}	980 mm^2
Total cross-sectional area of post-tensioning strands at bottom of beam, A_{ps2}	560 mm^2
Distance from top of beam to center of gravity of top strands, x_{ps1}	150 mm
Distance from bottom of beam to center of gravity of bottom strands, x_{ps2}	150 mm
Ratio of initial post-tensioning jacking stress to the ultimate strength of the strands	0.50
Drift demand at design earthquake level	0.020
Drift demand at maximum considered earthquake level	0.035
Unconfined concrete characteristic strength, f_{ck}	50 MPa
Confinement spiral diameter and spacing	Φ8/50mm
Confinement stirrups diameter and spacing	Φ12/100mm
Concrete cover	50 mm
Longitudinal reinforcement at beam end	10Φ26

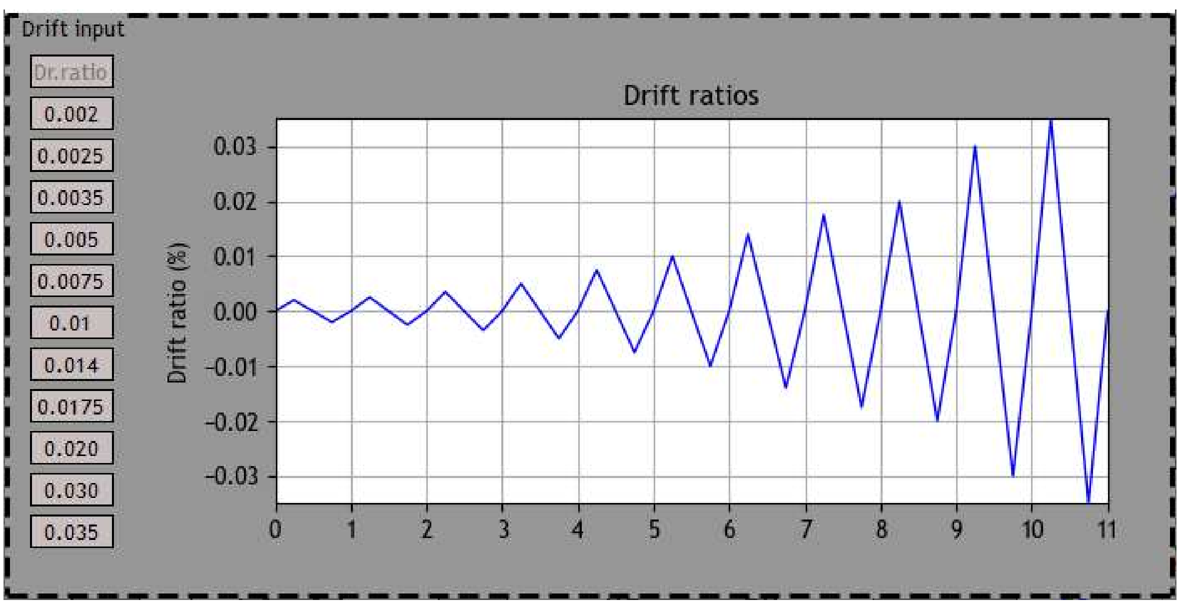
Results shown above are used to analyze the joint. The input values are entered in the Input Tab as explained in detail in Section 2.



The input parameters that are not self-explanatory are described as follows:

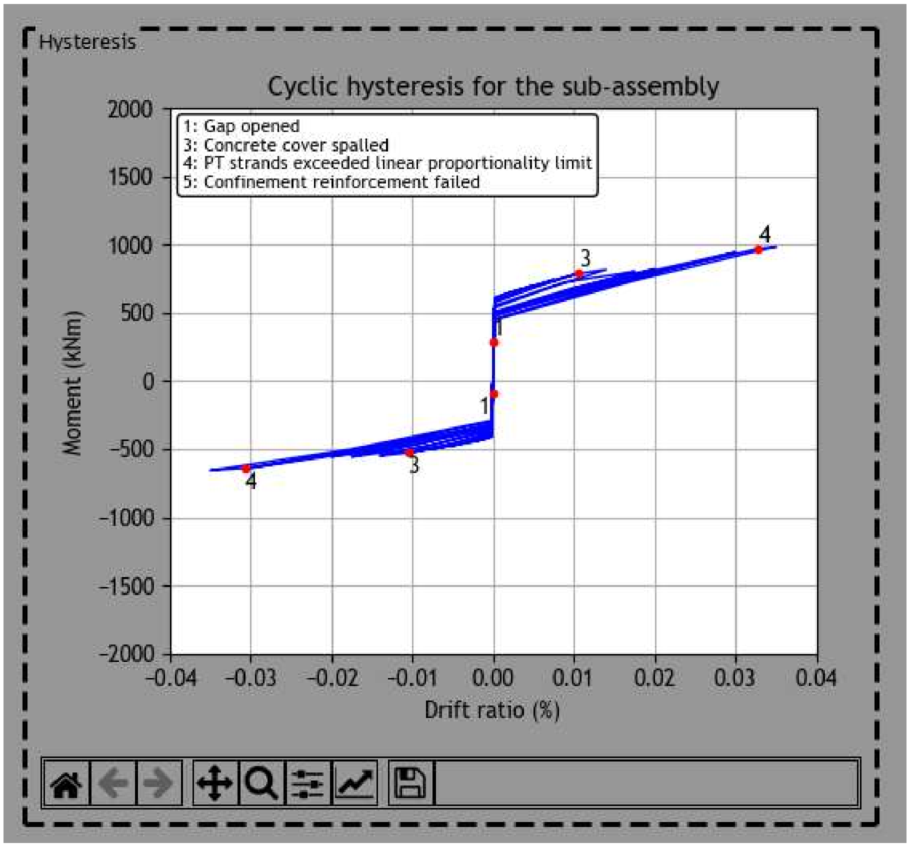
L_b = (8,000mm-800mm)/2 = 3,600mm

L_{drifts} (list of drifts to be applied) include drift demands, 0.020 and 0.035:



Overview of results

The moment-rotation hysteresis and the summary table is shown to interpret the results from an overall perspective.



Positive direction performance report:

Performance point	Drift ratio (%)	Moment (kNm)
1: Gap opening started	-	288.9
3: Cover concrete spalled	0.01050	787.7
4: PT strands exceeded linear proportionality limit	0.03281	972.1
5: Confinement rebars failed	-	-

Negative direction performance report:

Performance point	Drift ratio (%)	Moment (kNm)
1: Gap opening started	-	-93.4
3: Cover concrete spalled	-0.01050	-527.6
4: PT strands exceeded linear proportionality limit	-0.03063	-640.4
5: Confinement rebars failed	-	-

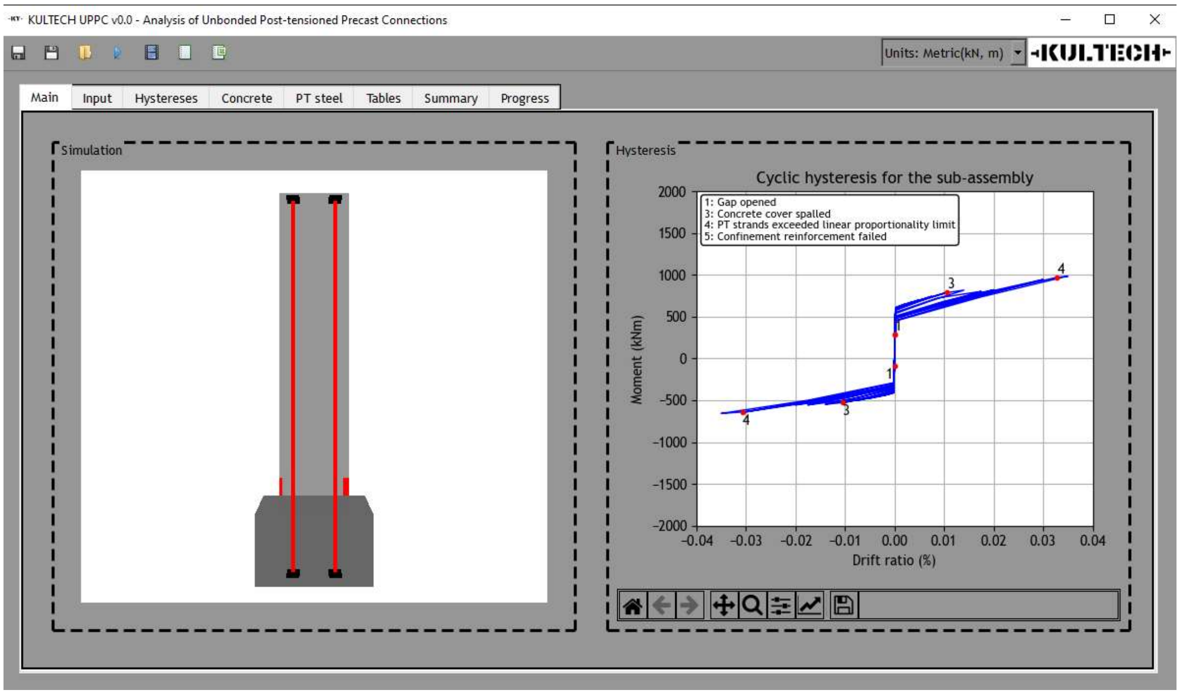
Energy dissipation parameters:

Drift ratio	Relative Energy Dissipation Ratio, β	Equivalent Viscous Damping Ratio, ξeq
0.00200	0.00224	0.00015
0.00250	0.00000	0.00000
0.00350	0.00040	0.00002
0.00500	0.00091	0.00003
0.00750	0.00383	0.00008
0.01000	0.00753	0.00013
0.01400	0.02220	0.00030
0.01750	0.02792	0.00032
0.02000	0.01452	0.00015
0.03000	0.01577	0.00013
0.03500	0.01461	0.00011

- Gap opening for the positive direction (please note that this direction is the one which corresponds to negative moment in the global composition of the beam) initiates at M = 288 kNm. This means that there is no gap-opening at design gravitational loads (M_{DGR}^{-} = 270 kNm < 288 kNm) which is the desired behavior.
- The average equivalent viscous damping ratio is 0.01 %, which is significantly smaller than the 5.00 % value assumed in spectral analysis that was done in preliminary design. This alarms the user that the lateral seismic demands in preliminary design is underestimated. The scaling of design spectra according to equivalent viscous damping ratio is beyond the scope of this document and can be found in literature. [5]
- Although the drift ratio concept in KULTECH UPPC is equivalent to joint rotation and it cannot be directly related to the rotation demand imposed on the joint in global structural model, it can give an idea to the user about performance levels of this joint. The joint will be in Immediate Occupancy Performance Level until the negative moment reaches 289 kNm or positive moment reaches 93 kNm, in Life Safety Performance Level until the negative rotation reaches 1.05 % or positive rotation reaches 1.05 %, in Collapse Prevention Performance Level until the negative rotation reaches 3.28 % or positive rotation reaches 3.06 %. (Please refer to Appendix A for a detailed explanation of performance levels for UPPC systems)
- The post-tensioning strands remain elastic well beyond design earthquake rotation demands, which is crucial in self-centering aspect of these systems.

Defining of moment-rotation relationship to global analysis program

As was mentioned, nonlinear static or dynamic analyses are required to capture the seismic behavior of UPPC systems. In order to perform a realistic nonlinear analysis, KULTECH UPPC results are used to define the moment-rotation relationship of the joint to the structural analysis program being used in the global nonlinear structural analysis of the building.



To export the results to MS Excel for post-processing, click on the Export to Excel button on the toolbar. Below is shown a spreadsheet sample of results obtained for this example.

Step	Drift(%)	M(kNm)	c(mm)	εcj	fcj(MPa)	foct(kN)	εps1	fps1(MPa)	fops1(kN)	εps2	fps2(MPa)	fops2(kN)
0	0	0	800	0	0	0	-0.0047	-930.8	-912.2	-0.0047	-930.8	-521.3
1	0.0002	608.8	134.9	0.001032	35	1437	-0.0047	-935.5	-916.8	-0.0047	-931	-521.3
2	0.001	627.3	120	0.00119	39.3	1457.7	-0.0048	-954.7	-935.7	-0.0047	-932.2	-522
3	0.002	648	107.6	0.001373	43.6	1483.6	-0.0049	-979.8	-960.2	-0.0047	-934.7	-523.4
4	0.0018	643.8	109.9	0.001341	42.4	1478.3	-0.0049	-974.7	-955.2	-0.0047	-934.1	-523.1
5	0.001	626.3	121.3	0.001203	37.5	1457.6	-0.0048	-954.7	-935.6	-0.0047	-932.1	-522
6	0.0002	606.7	137	0.001048	32.1	1436.7	-0.0047	-935.5	-916.7	-0.0047	-930.9	-521.3
7	0	-23.1	800	0.000041	0.1	1433.5	-0.0047	-930.8	-912.2	-0.0047	-930.8	-521.3
8	-0.0002	-411.6	136.1	0.000011	0	1434.1	-0.0047	-931	-912.3	-0.0047	-935.5	-523.9
9	-0.001	-425.4	120.7	0.000011	0	1448.1	-0.0047	-932.1	-913.5	-0.0048	-954.7	-534.6
10	-0.002	-440.1	107.9	0.000011	0	1464.6	-0.0047	-934.6	-915.9	-0.0049	-979.8	-548.7
11	-0.0018	-437.2	110.3	0.000011	0	1461.2	-0.0047	-934.1	-915.4	-0.0049	-974.7	-545.8
12	-0.001	-424.5	122	0.000011	0	1448.1	-0.0047	-932.1	-913.4	-0.0048	-954.7	-534.6
13	-0.0002	-409.4	138.5	0.000011	0	1436.2	-0.0047	-930.9	-912.3	-0.0047	-935.4	-523.8
14	0	11.7	800	0.000041	0.9	1433.5	-0.0047	-930.8	-912.2	-0.0047	-930.8	-521.3
15	0.0002	604.1	140	0.001071	31.2	1435.6	-0.0047	-935.4	-916.7	-0.0047	-930.9	-521.3
16	0.00125	629.4	119.6	0.001272	37.1	1463.8	-0.0048	-960.7	-941.5	-0.0047	-932.5	-522.2
17	0.0025	657.9	103.2	0.001463	45.3	1496.9	-0.005	-992.5	-972.7	-0.0047	-936.1	-524.2
18	0.0023	653.8	105.2	0.001432	44.2	1491.5	-0.005	-987.4	-967.6	-0.0047	-935.5	-523.9

CSI SAP2000 is the global structural analysis program chosen to illustrate the moment-rotation definition. (Please refer to CSI SAP2000 documentation for more information on the SAP2000 modules that will be mentioned) There are two options to analyze the global structure:

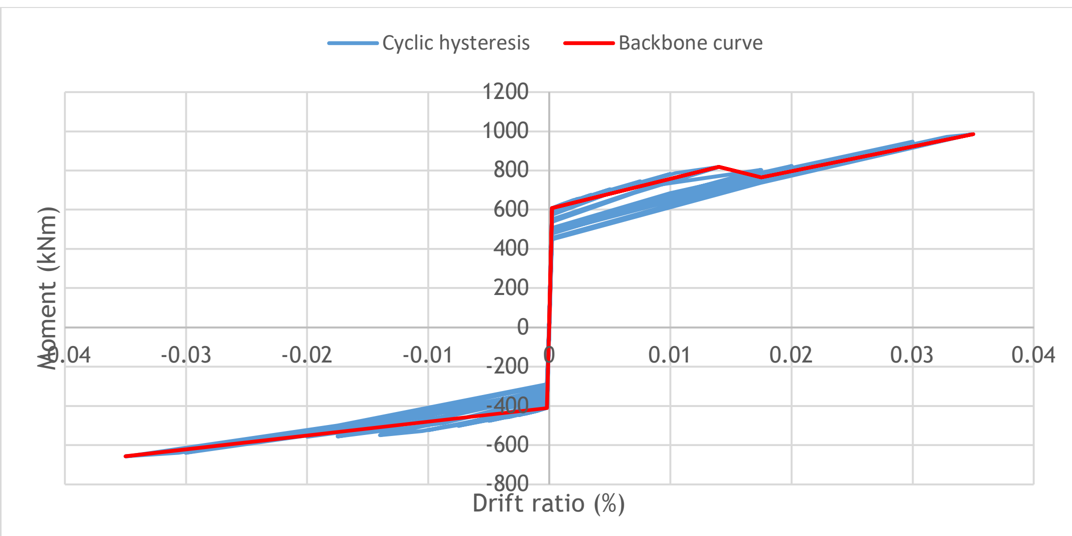
1. Nonlinear static monotonic analysis (Pushover)
2. Nonlinear dynamic time-history analysis

For both of these methods, the unique nonlinear behavior of UPPC systems are taken into account by the following two steps:

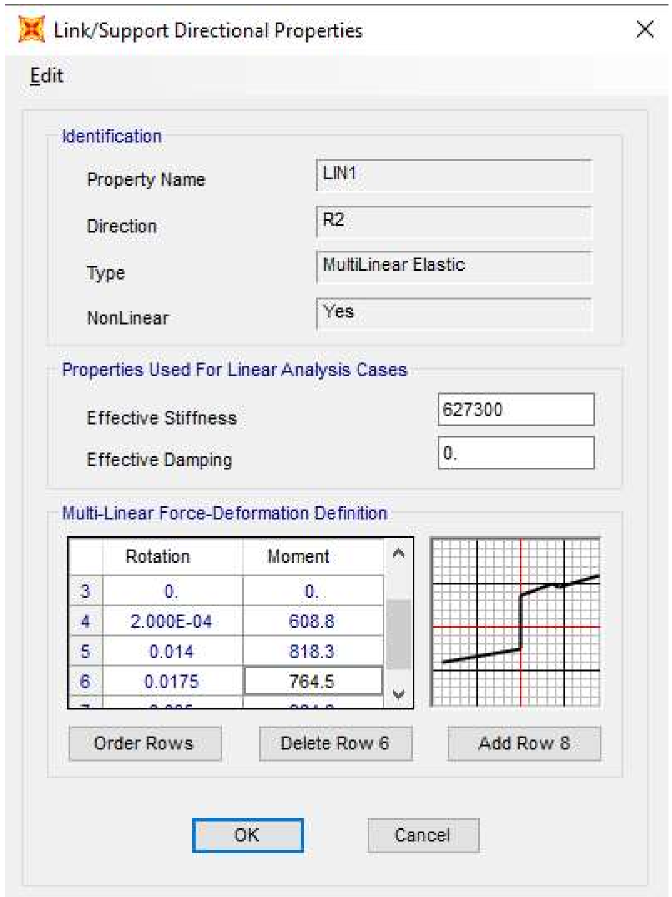
1. The nonlinear behavior of the joint will be modelled by a link, not a hinge. The reason is that the multi-linear (almost) elastic moment-rotation relationship can only be defined in a link in SAP2000.

2. The limited energy dissipation capacity of the system will be taken into account by scaling the earthquake spectra with respect to the 5% equivalent viscous damping ratio that is typically used in reinforced concrete structures.

Define the backbone curve of KULTECH UPPC moment-rotation results in your Multilinear Elastic Link module in the R2 direction (this depends on your axes).



Backbone curve obtained from KULTECH UPPC results



Definition of backbone curve in the Multilinear Elastic Link

In the analyses, the designer should also take into account the lack of energy dissipation in Unbonded Post-tensioned Precast Systems. To do this, the design earthquake spectra should be scaled according to the equivalent viscous damping ratio calculated in KULTECH UPPC. This is beyond the scope of this document, but the reader is referred to Reference [5].

After the analysis is carried out, the rotation demands on the joints can be used to assess the performance levels of the joints (the limit states are given by KULTECH UPPC) and a global performance level assessment can be done.

4. References

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5. 'Dynamics of Structures: Theory and Applications to Earthquake Engineering'. Chopra A.K., Pearson Prentice Hall, 3rd Edition.

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Appendix A: Why UPPC Systems are Unique

'Strength is essential, otherwise unimportant.'

Hardy Cross

Summary

Traditional structural seismic design approach is to design buildings so they behave inelastically and to provide sufficient ductility to prevent brittle failure of structural members, joints, and eventually the whole system. The inelastic behavior of buildings manifests itself by way of significant structural damage post-earthquake. This structural damage can at times require very high repair costs or can prevent functionality of the building for a considerable time. Rather than designing the building to have structural damage which is to be repaired later, recent advancements in earthquake engineering include increasing use of low-damage design philosophy. Low-damage design is by definition designing buildings so there is minor, negligible or easily repairable structural damage in a building subjected to design level earthquake. One of the most efficient low-damage seismic systems is Unbonded Post-tensioned Precast Concrete (UPPC), in which structural damage is concentrated in a specially designed joint interface. Moreover, post-tensioning strands are designed to remain elastic, which causes the building to re-center after the seismic event, thus minimizing residual deformations. However, this system has unique aspects which prevent it to be modelled and analyzed with conventional methods and computer software. In addition, performance criteria cannot be defined for these systems as it is defined for conventional systems. The gap-opening behavior, un-bonded nature of strands and low energy dissipation capacity require special analytical and modelling techniques for these systems. This article explains in detail the peculiarities of Unbonded Post-tensioned Precast Concrete systems and introduces the reader to a computer program written to obtain their moment-rotation behavior.

What is Low-damage Design?

Structural engineers are responsible for designing structures to withstand any loads they are likely to be subjected to, and they are professionally obliged for doing it in the most economical way.

Consider the force-deformation relation given for a structural system in Figure A1. Theoretically it is possible to design any type of building to behave elastically when subjected to design earthquake, but for most situations it is economically not viable.

Mainly for this reason (and for other reasons we will mention later) the conventional design philosophy is to let the building to 'yield', but make sure it does not fail in a brittle manner (provide sufficient ductility).

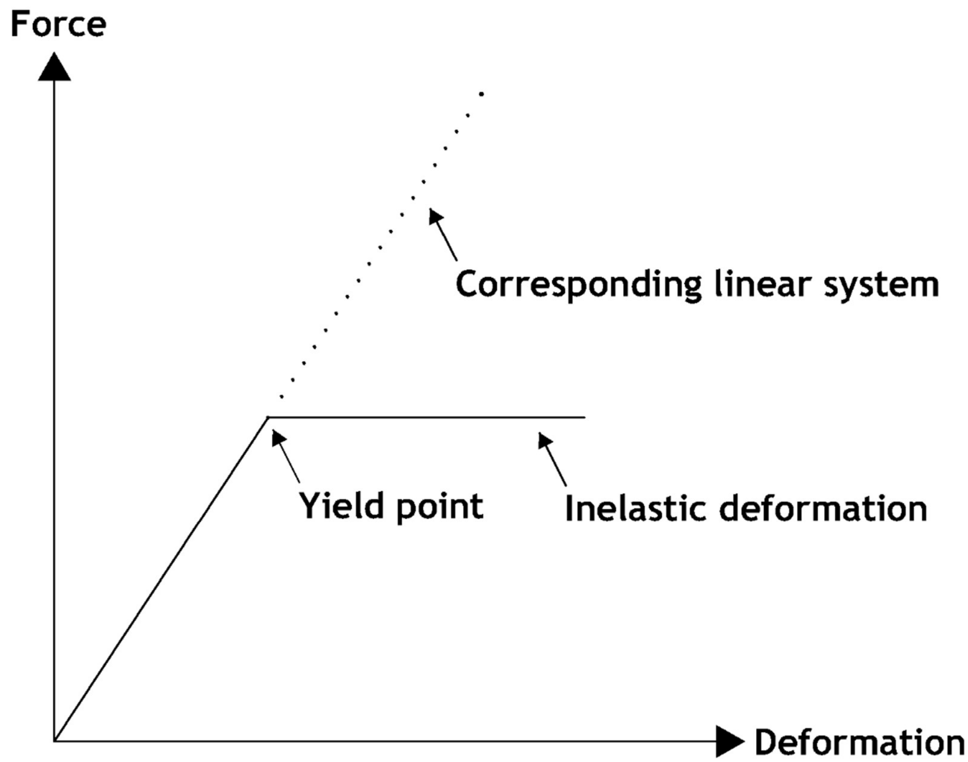

Figure A1 – Idealized bilinear elasto-plastic behavior of structural systems

Letting the building to yield obviously means letting it have inelastic deformations. Inelastic deformations are by definition residual, which means they remain after the earthquake. The state of the building in terms of the level of structural damage is defined by a concept called Performance-Based Seismic Engineering, but this topic is beyond the scope of this article. We will suffice in stating that taking into acount various parameters (occupancy type etc..) the seismic performance is evaluated according to structural damage level. In other words, structural damage IS allowed in most cases in seismic design.

If the building in question is a production facility that cannot tolerate a temporary closure for retrofit operations, or a residential building for that matter, repairing structural damage sounds not feasible. So why not design the building from the beginning to have minimum structural damage that does require very little repair operation or no repair at all?

The Most Beautiful Low-Damage System: UPPC

Enters to the scene a beautiful structural system: Unbonded Post-tensioned Precast Concrete, UPPC.

First, let's examine a little more closely where structural damage occurs in conventional cast-in-situ reinforced concrete buildings. For brevity, let's focus on a relatively simple (isostatic) cantilever beam. For further brevity, let's consider applying an incremental vertical static load at the top of the beam. Reinforcing steel at the bottom is mainly constructive, hence the primary tensile reinforcing steel is the one at the top. (Figure A2)

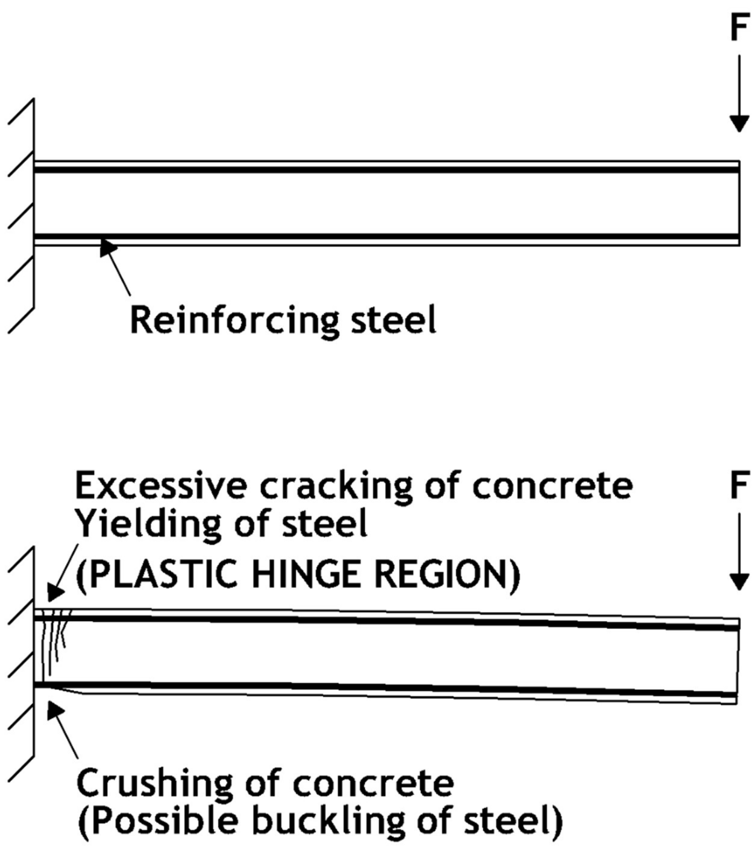

Figure A2 – Plastic hinge region of a cantilever beam with point force at the end

When the beam reaches its yield point, much of further deformation that takes place is inelastic(plastic). This plastic deformation is distributed to a length which is called *plastic hinge length*. Within this plastic hinge length and not necessarily confined to it, inelastic deformations are exhibited in the beam member, protruding to a significant distance towards mid-span. These inelastic deformations are predominantly yielding of mild steel and cracking or spalling of concrete. An example of such deformations can be observed in Figure A3a.

One last thing to stress about this conventional joint is that it is basically monolithic, which means that the beam-column joint is (in most cases assumed to be) full rigid and that structural damage is not concentrated to a surface but propagates to a significant length.

Now let's move directly to Figure A3, which clearly demonstrates the difference between structural damage observed in cast-in-situ joint and UPPC joint.

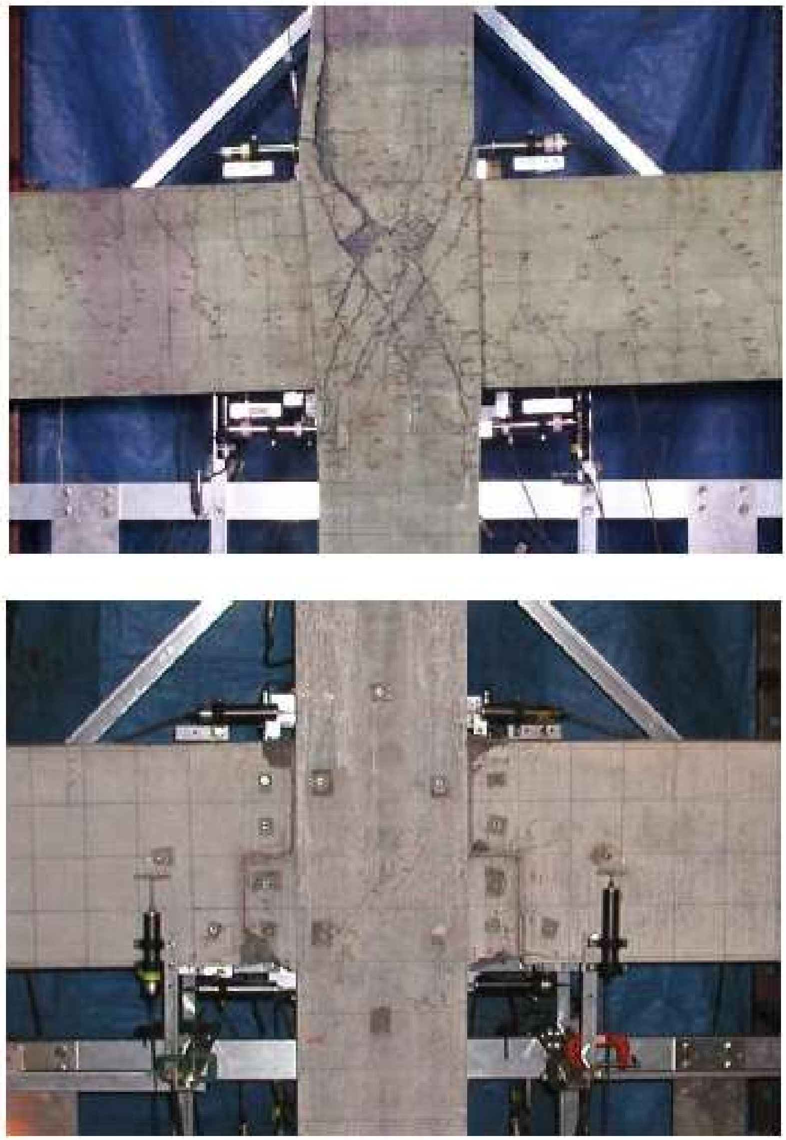

Figure A3 – Structural damage at a) Cast-in-situ joint b) UPPC joint [1]

As can be clearly observed, structural damage is concentrated at local joint interface in UPPC and it is much lighter than the substantial damage in cast-in-situ joint, which shows itself mainly in joint panel region and proceeding towards column member.

What makes UPPC unique?

Let's look at the unique characteristics of UPPC which make them low-damage systems.

Gap-opening

One of the first things that are taught in reinforced concrete courses is that 'plane sections remain plane'. It comes with 'strain compatibility' principle, which assumes there is perfect bonding between reinforcing steel and concrete. This phenomenon allows the analyst to equate the strain at concrete fiber at rebar level to rebar strain.

Let's consider the cantilever beam once again. Figure A4 illustrates the strain compatibility principle and section equilibrium for a cast-in-situ joint interface/section. Please note that unconfined and confined concrete distinction is not displayed for brevity.

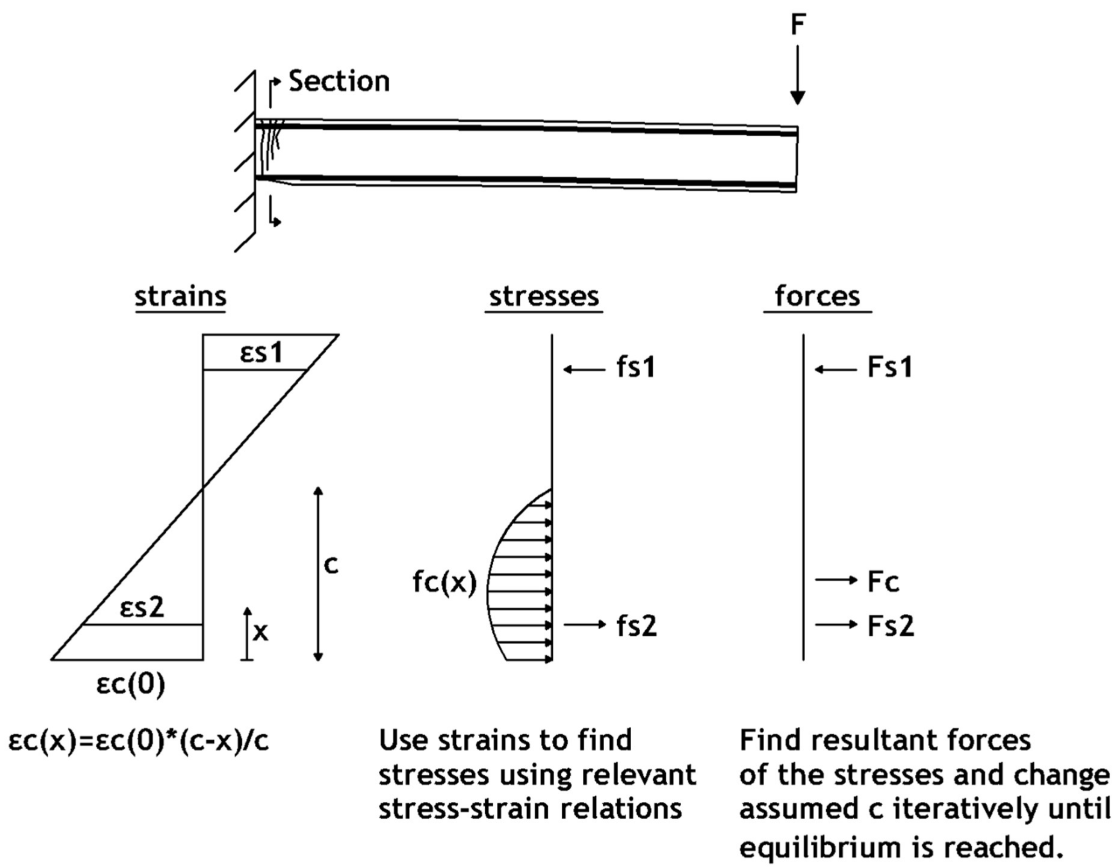

Figure A4 – Section analysis parameters for conventional member section

This phenomenon does not apply to UPPC systems. Precast systems, by definition, are produced as individual members in the production facility and they are connected at the site. Although it is possible to design and construct them 'emulating' monolithic construction, this is not the case in UPPC systems. In UPPC systems, individual precast members (mainly beams and columns) are connected by post-tensioning strands which typically have no anchorage to the members along the length. When the load is applied at the tip of the cantilever beam, a gap opens at the beam-column joint interface, imposing elongation at the post-tensioning strands. There is no strain compatibility. Figure A5 illustrates the gap-opening concept.

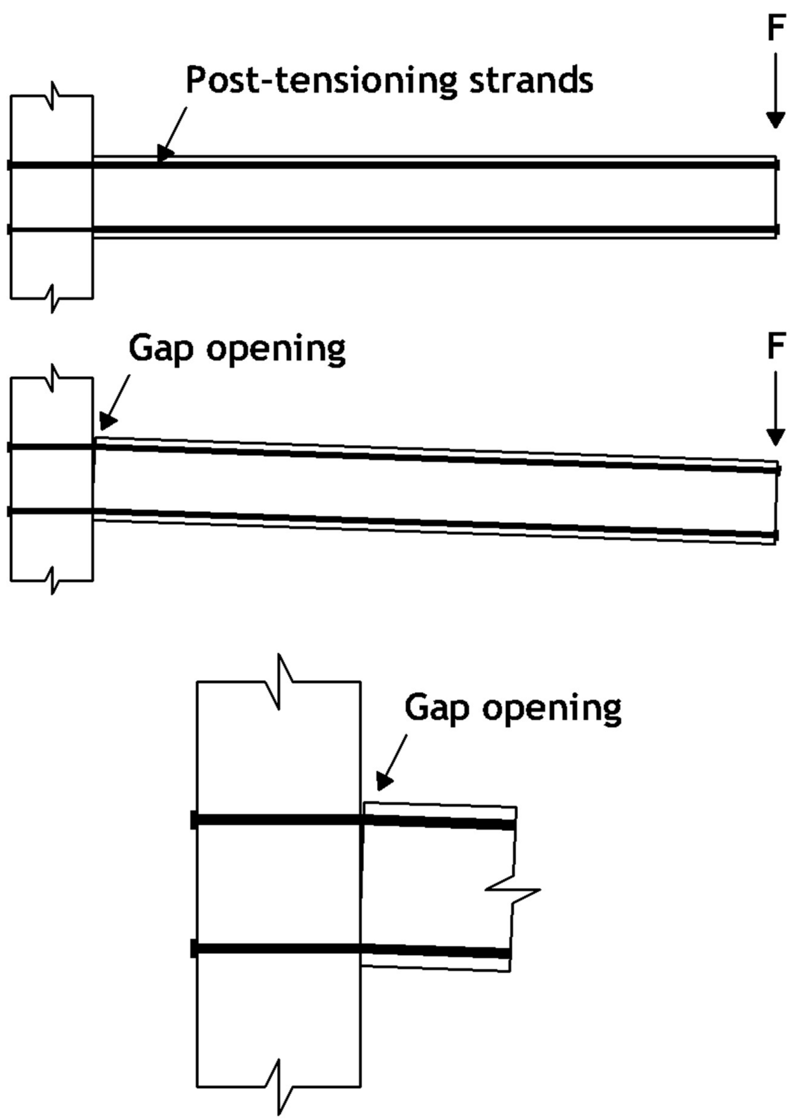

Figure A5 – Gap opening in UPPC systems

When seismic forces impose gap opening at the joint, tensile stresses are resisted by the post-tensioning strands. Compressive stresses are resisted by concrete reaction forces, which cause stress concentrations near the joint region. This joint region is typically specially designed (using fiber reinforced concrete or alternative materials) to reduce the structural damage to a tolerable degree. Furthermore, post-tensioning strands are designed to remain elastic under design earthquake demand, which enables them to 'self-center' the system.

Elastic post-tensioning strands

The post-tensioning strands can be considered as a nonlinear elastic truss member because they are not bonded to the surrounding members throughout their length. Obviously, the forces acting on them are a function of the stresses acting on them, which in turn are a function of the longitudinal strains they have. These longitudinal strains can be easily calculated by the basic strain relation (See Figure A6):

$$\varepsilon = \frac{\Delta_L}{L_i}$$

Where ε is the longitudinal strain in the strands, Δ_L is the total change in length of the strand (in our case always elongation), and L_i is the initial length of the strand between the anchorages.

The logic of prestressing comes with the fact that the strands are by definition 'pre'stressed. In other words, they have an initial longitudinal strain ε_i due to jacking before any forces act on them. The gap-opening imposes additional strains on them, as shown in Figure A6.

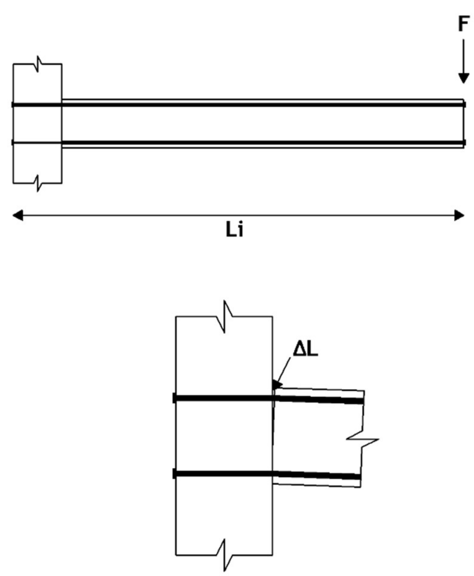

Figure A6 – Strain imposed on strands by gap opening

The stress-strain relation for pre-stressing strands is given in Figure A7. [2] As can be seen, when the proportionality strain limit is exceeded, we can no longer talk about elasticity in the strands. However, elasticity can be described as 'tendency to take original shape after the forces are removed'. And in our case it is particularly useful because if we make such a design that the strands are still in the elastic range at design earthquake level, we can achieve 'self-centering' effect which dramatically reduces residual deformations. This is one of the phenomena which make UPPC low-damage systems.

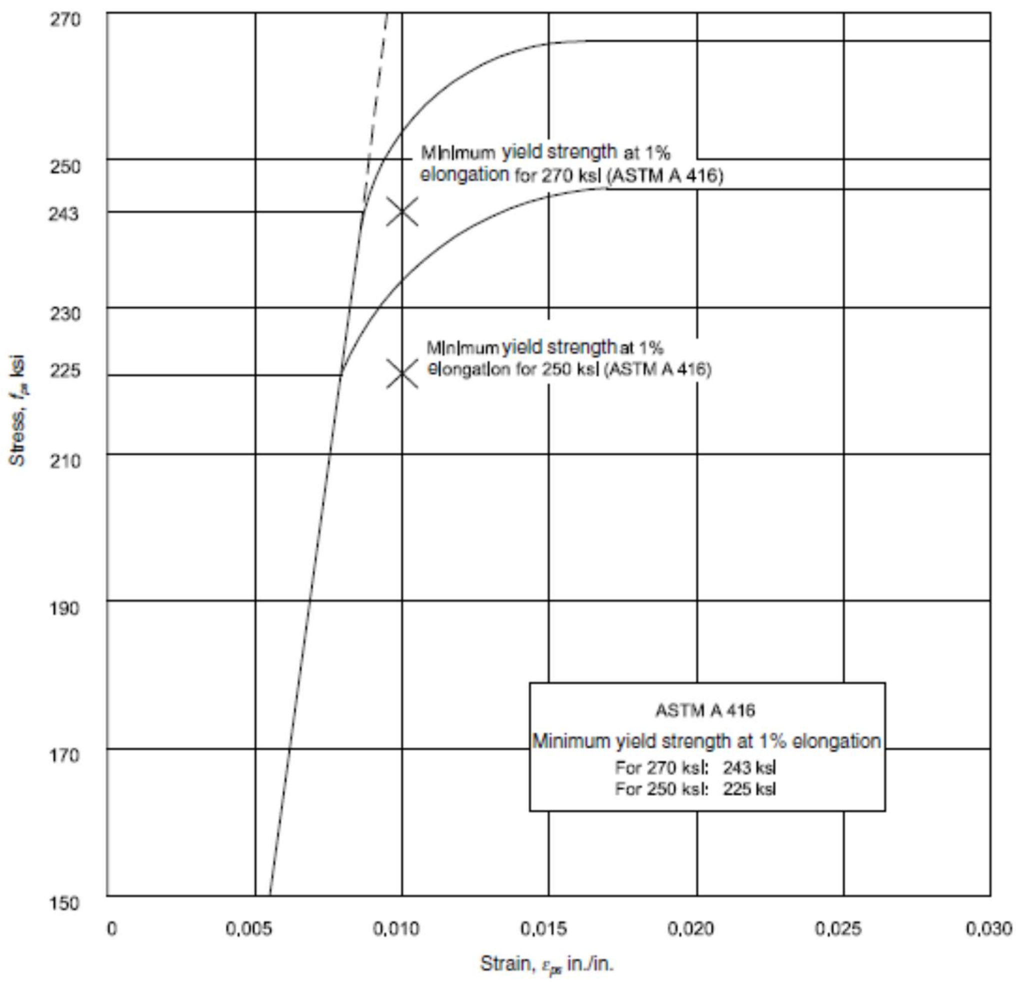

Figure A7 – Stress-strain relation for prestressing steel

One last thing to point out about post-tensioning strands, in UPPC systems where strands are placed at top and bottom of the beam, because strain demands are high due to the location of the strands, the initial jacking stress is limited to 50% of the ultimate strength.

Equivalent viscous damping ratios ξ_{eq}

Since damping is a phenomenon which is extremely difficult to quantify and idealize, common practice is to use assumed values for it. The widely accepted equivalent viscous damping ratio for conventional reinforced concrete structures is 5.00%. However, this number generally does not apply for UPPC systems, since they have lower energy dissipation capacity than cast-in-situ systems. Since these systems are by definition 'low-damage', the mechanisms which are assumed to take place in reinforced concrete systems to possess ξ_{eq} of 5.00% are not present for them. For this reason, the equivalent viscous damping ratios for these systems should be calculated exclusively.

The equivalent energy dissipation ratio ξ_{eq} is given by Chopra [5] with the following relation:

$$\xi_{eq} = \frac{1}{4\pi}\frac{E_D}{E_{so}}$$

This energy dissipation issue is very important and it will be covered in detail in the next article. The parameter defined by ACI T1.1-01 [6], relative energy dissipation ratio β will also be discussed in detail in the upcoming article.

Performance criteria for UPPC systems

Performance criteria specified by international building codes to determine seismic performance level of structures cannot be used for UPPC systems because of the unique aspects we have outlined. For this reason, special performance criteria for UPPC systems should be defined.

Before outlining performance criteria, let us examine the 5 limit states a typical UPPC moment-rotation curve has. El-sheikh et al [3] define these limit states as follows:

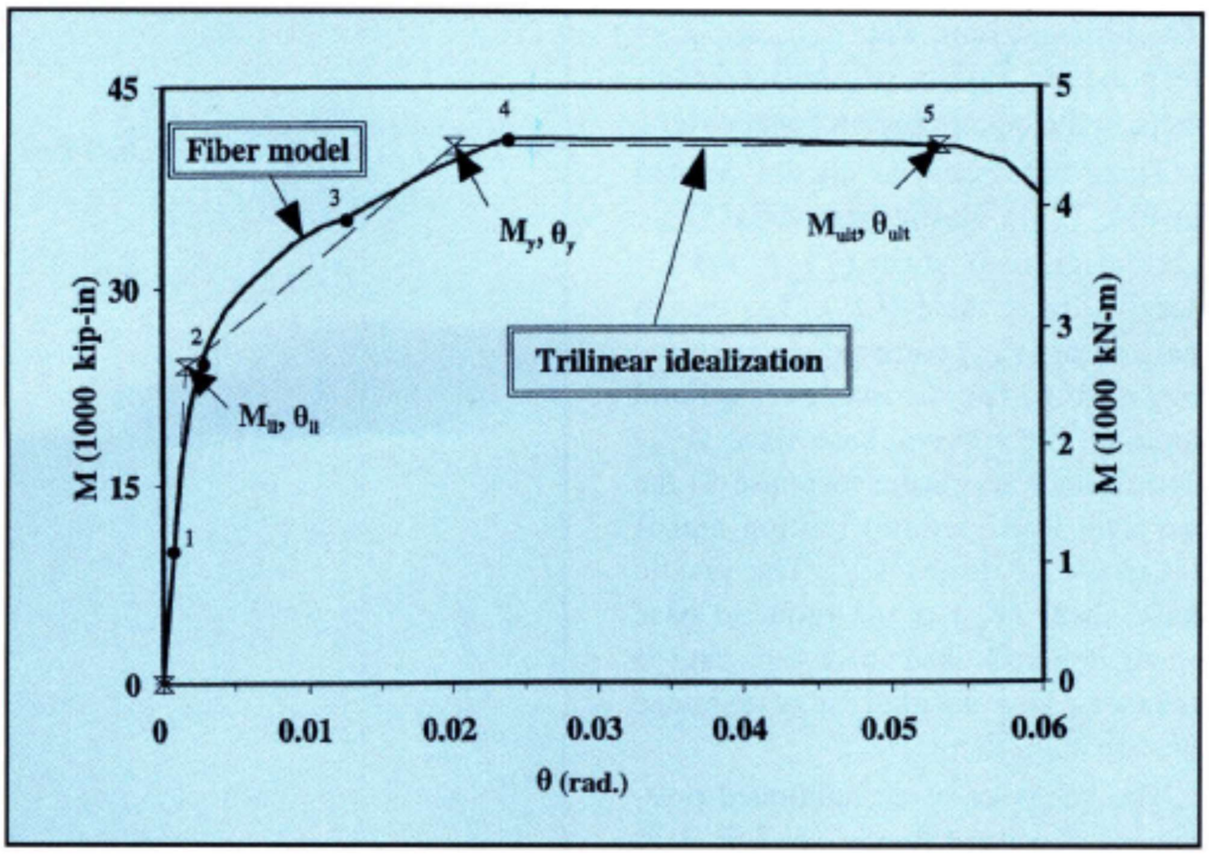

Figure A8 – Typical moment-rotation curve for UPPC [3]

State 1: Decompression limit state. Gap-opening begins. Beyond this point moment-rotation behavior is softened due to a) propagation of gap opening along the section b) an increase in concrete stress and strain which softens concrete

State 2: Linear limit state. After this point moment-rotation behavior significantly deviates from the initial linear part.

State 3: Cover spalling limit state. The state at which unconfined concrete cover spalls. Rapid decrease in unconfined concrete stress occurs, which decreases the slope of the moment-rotation curve.

State 4: Yield limit state. Post-tensioning strand reaches the limit of proportionality, beyond which point strands begin to deform inelastically.

State 5: Ultimate limit state. Strain at the extreme fiber of confined concrete reaches its ultimate strain. Confining reinforcement fails. A brittle failure is expected.

Now let us see how Kurama [4] defines performance criteria for UPPC systems:

Immediate Occupancy Performance Level:

- Decompression at beam-column interface (State 1)
- Slip of friction dampers (This is specific to the case with dampers)
- Hairline cracking near beam-to-damper and column-to-damper connections (This is specific to the case with dampers)

Life-safety Performance Level:

- Crushing of unconfined concrete (State 3)
- Flexural hinging at column base

Collapse Prevention Performance Level:

- Yielding of post-tensioning strands (State 4)
- Confined concrete on the verge of crushing (State 5)

Analytical modelling of UPPC systems

The gap-opening behavior and the unbonded post-tensioning strands also require unique modelling techniques to represent the behavior of UPPC systems in the most correct way. Kurama [4] once again provides very useful insight into how to model such systems. In this article, we will only mention two principles which are essential to the unique aspects we have mentioned.

The most realistic way to model post-tensioning tendons is to model them as truss members with bilinear stress-strain relationship. The location of the truss member is chosen according to the location of the strands with respect to section's neutral axis. The jacking stresses can be modelled as initial internal stresses. The anchors of strands are modelled by kinematically constraining truss nodes at the end to the relevant nodes at beam ends.

The gap-opening behavior is modelled by equating tensile strength and stiffness of concrete fibers to zero. This way, the reduction of stiffness due to gap opening is taken into account by the fact that concrete fibers subjected to tensile strains have no stiffness.