LECTURE : Understanding Staged construction In Buildings using SAP2000

AUTHOR :   Carlos Ferreira
carlos@csiberkeley.com

DATE: 30-07-2008

GOALS: Understanding the SAP2000 staged construction analysis.

                Learning how to deal with SAP2000 stage construction displacement results.

                Realizing the potential of this toll together with the time Dependent properties and Creep analysis.

Let's imagine a isolated concrete column, subjected to the construction process traditional in general buildings.

We will for now neglect the time dependent effects and the in-stage construction sequence.

We will assume that we have a target structure, as in the picture below, where each column of length **L** is in fact a storey of a building, **_and that in the whole construction process we are more interested in having each storey slab in the rigth elevation position, then rather having exact columns of length equal to L_**.
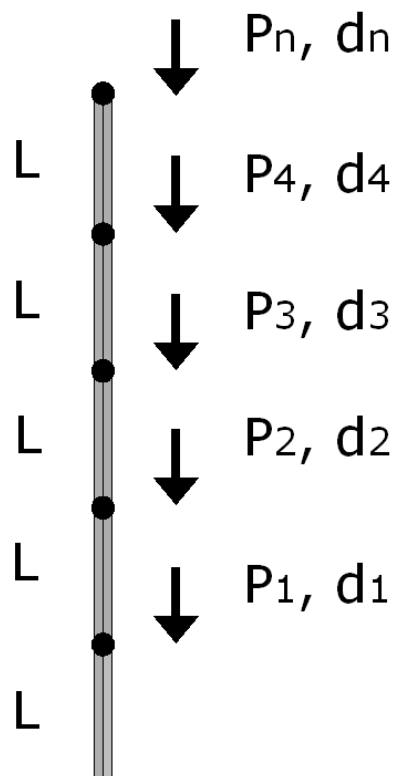
The stiffness of the column is **EA/L** , assuming that a given column has **L** as length.

Each column will be added stage by stage, and after each one is added the load **P** is added to the top of the column.

_P1=P2=P3 = Pn_

Each column top joint will have a joint displacement, **_d_**.

Concrete Column (EA)

P_n, d_n

L

P_4, d_4

L

P_3, d_3

L

P_2, d_2

L

P_1, d_1

L

L

The questions are:

a) How can we predict the Joint displacements for the staged analysis?
b) What are the hypotheses used in SAP2000?
c) How can we short verify the results?

In a brief way, we must emphasize that the purpose of staged analysis is exactly to be able to represent properly the construction process without having to suffer from accumulation of unrealistic displacements on the total building length, especially for the high rise buildings, and for the self weight and some permanent loads.

There is a major understanding that needs to be clarified:

When you add a storey as a stage, SAP will try to put the new joints that are not touching an old structure in the exact position of the unstressed initial model. This means that on each stage we are more focused on the position where the structure will be added rather than the exact length of the elements.

So, let's think about a way to get the behavior of this model in SAP2000.

Based on this previous statement we can write:

$$L_{k=}L + d(k-1) \qquad\qquad (1)$$

Where

L_k is the real length of an unstressed column when added to the stage k

L is the idealized length of each column

k is the stage index for which we are calculating the real column length

We also want to know what is the joint displacement in the top of a column, when this same column is added as a stage, and immediately applied the load P at the top.

We can then write:

$$d_k = \frac{P}{EA} \sum_{i=1}^{k} L_i \qquad\qquad (2)$$

Where

d_k is the vertical displacement in the column when the stage and load is added

P is the load for each storey

EA is the Young Modulus times the Area of the column

L_i is computed from the expression (1)

Now, in order to compute total displacement for each joint, we want to know how much each joint is displaced vertically, when it is added as a stage, but also when other stages above it are added. Because for instance the first column will be moving downward each time a stage is added, and of course, when the load of the first stage is set also.

So we can then get an idea of how much each joint displaces vertically when other stages are added by writing:

$$dst_{s,j} = d_s \, \frac{\sum_{i=1}^{j} L_i}{\sum_{i=1}^{S} L_i} \qquad (3)$$

Where

$dst_{s,j}$ is the displacement of the column j when the stage s is added

d_s is as computed in expression (2)

L_i is computed from the expression (1)

If we want to compute the total vertical displacement for a given column j when the stage n is added, then we can write:

$$td_{j,n} = d_j + \sum_{i=j+1}^{n} dst_{j,i} \qquad (4)$$

Where

$td_{j,n}$ is the total displacement of column j when stage n is added

d_j is as in expression (2)

$dst_{j,i}$ is as in expression (3)

As curiosity we if we would neglect the real length change in columns, we could write a simple:

$$td_{j,n} = P * \frac{n+1-j}{\frac{EA}{L*j}} \qquad (5)$$

So in order to understand the results that these expressions can bring to us, we will create a real example:

```
L = 3  ' columns with 3 meters
P = 300  ' kN
EA = 30.5 * 10 ^ 6 * 0.3 * 0.3  ' concrete with a 0.3 x 0.3 column
nStages = 10
```

To do so, we use a very simple Excel Macros and functions:

```vba
'=================================================
Dim L As Double
Dim P As Double
Dim EA As Double
Dim nStages As Integer
'=========================================================
' function to calculate the Length of the column when it is added to a stage
Function L_stage(k As Integer) As Double
    L_stage = L + D_stage(k - 1)
End Function
'=========================================================
' function to calculate the displacement of the top of the column when its own stage is added
Function D_stage(i As Integer) As Double
    Dim sum As Double
    Dim k As Integer
    sum = 0
    For k = 1 To i
        sum = sum + L_stage(k)
    Next k
    D_stage = P / EA * sum
End Function
'=========================================================
' Function to calculate the displacement in the top column j when added stage i
Function D_stage2(i As Integer, j As Integer) As Double
    Dim sumi As Double
    Dim sumj As Double
    Dim k As Integer
    sumi = 0
    sumj = 0
    For k = 1 To i
        sumi = sumi + L_stage(k)
    Next k
    For k = 1 To j
        sumj = sumj + L_stage(k)
    Next k
    D_stage2 = D_stage(i) * sumj / sumi
End Function
'=========================================================
' function To get max displacement at top joint of column i at a given stage
Function Max_D(i As Integer, stage As Integer) As Double
    Dim k As Integer
    Max_D = 0
    If stage >= i Then
        Max_D = D_stage(i)
        For k = i + 1 To stage
            Max_D = Max_D + D_stage2(k, i)
        Next k
    Else
        MsgBox ("Cannot calculate")
    End If
End Function
'=========================================================
```

```
' MAIN EXECUTION PROGRAM
Sub MACRO()

  L = 3  ' columns with 3 meters
  P = 300  ' kN
  EA = 30.5 * 10 ^ 6 * 0.3 * 0.3  ' concrete with a 0.3 x 0.3 column
  nStages = 10

  Dim k As Integer
  For k = 1 To nStages
     Worksheets(1).Cells(k + 1, 1) = L_stage(k)
     Worksheets(1).Cells(k + 1, 2) = D_stage(k)
     Worksheets(1).Cells(k + 1, 3) = Max_D(k, nStages)
  Next
End Sub
```
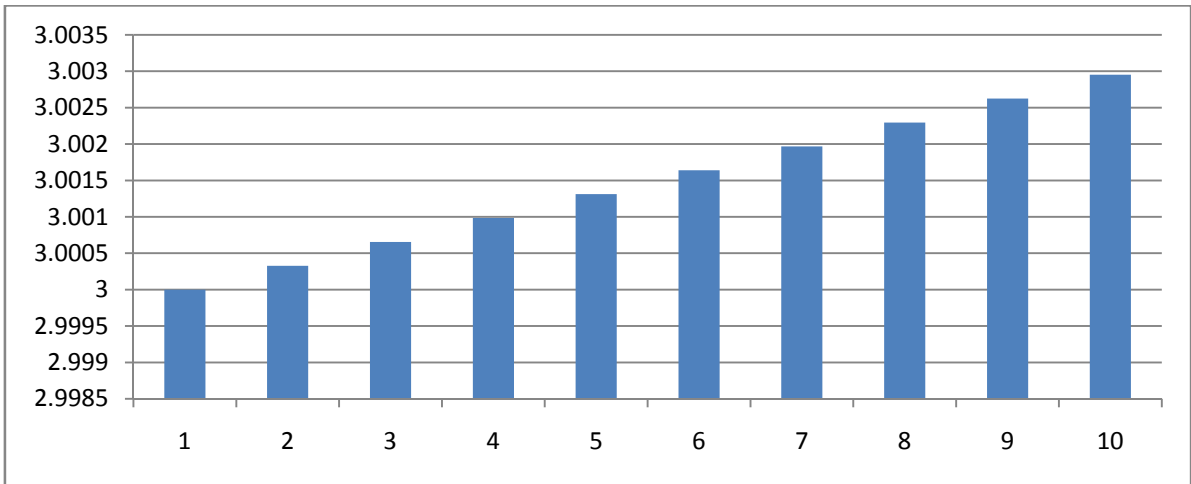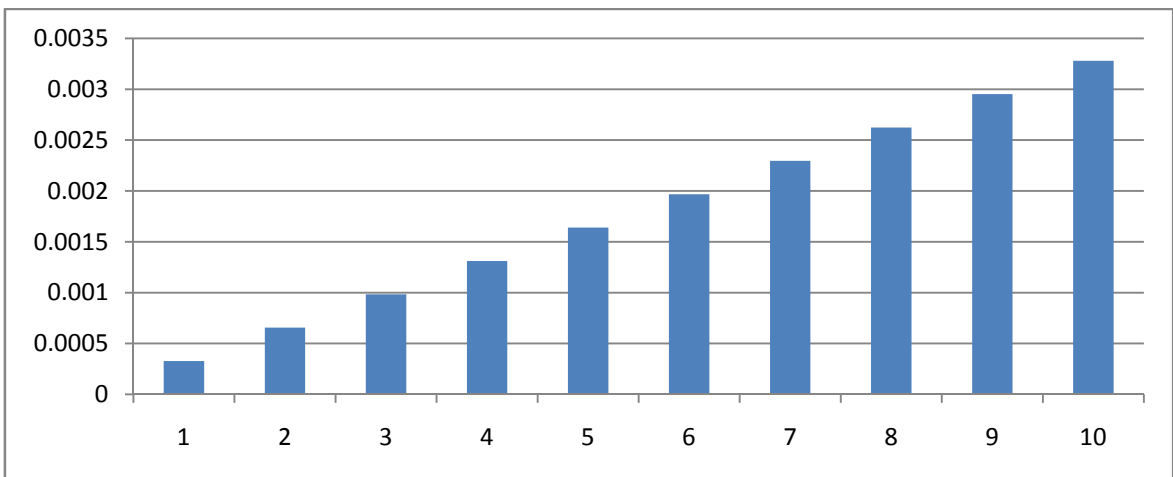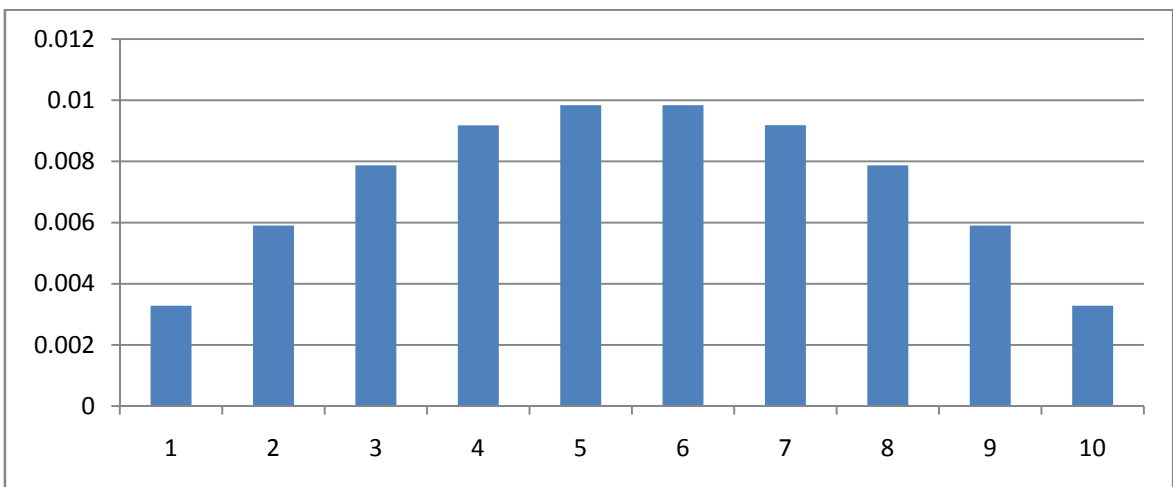
The results using MACRO we obtained in the EXCEL worksheet are quite interesting:

Real Unstressed column length for the columns of each storey

Displacement in the top of each column when added as a stage and then its own load

The total vertical displacement of each column in the end of final stage

As we can see the vertical displacement in the end of the stages has a quite unusual behavior as compared to the traditional displacement we are used to have if we do add the entire load to the whole structure at once.

It is very important to understand this properly for several reasons:

1 – First because Staged construction is a very powerful tool, that has to be used with confidence, and we should get a complete clear picture of the way it works internally in SAP2000.

2 – If we do add the time dependent properties, we will be adding creep, shrinkage and eventually relaxation, and these effects because of their slightly complicated and non linear nature, should be analyzed or compared with a very clear and linear situation that we do understand, in order to grasp the real time dependent effects. All that we did here is Linear Static Analysis, even if inside SAP2000, it is used the non linear engine when staged analysis is performed.

3 – These effects can be tremendously important in high rise buildings and in buildings with discontinuous vertical elements. Not using these features can lead to errors that might be important to the structure, if not accounted otherwise.

4 – These effects are very important for studying and monitoring the relative vertical behavior of elements of each storey, that when using time dependent properties and a long analysis time, like 30 years, can, in a relatively accurate way, predict the eventual cracking or force distribution that may be needed for ULS accounting.

5 – It is not evident at the beginning why the floors that deflect more are in the middle. The effect of artificial length increase in members and total weight that really deforms structure are important things to understand it.

Just as a matter of curiosity we plot here the traditional displacement of the 10 storey building with a linear static normal analysis versus the previous result of the staged construction analysis:
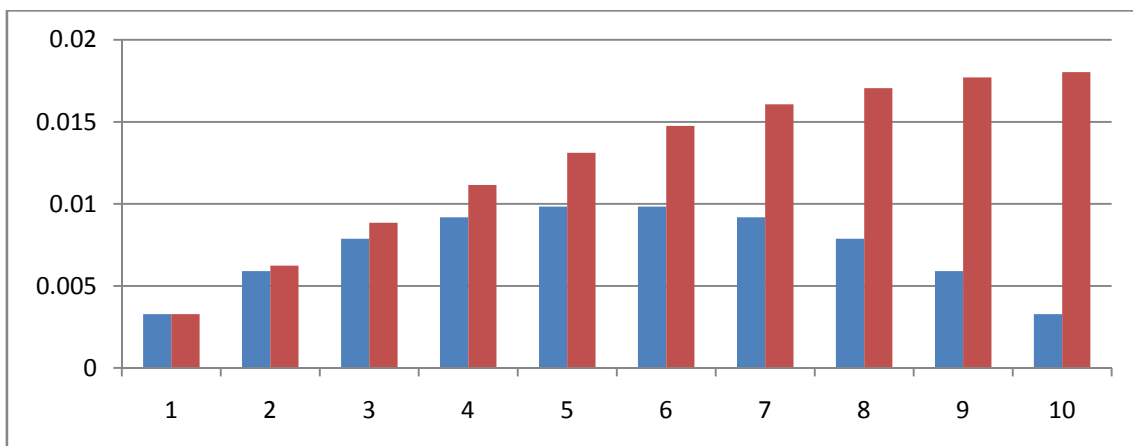
As you can see the displacement behavior is much different.