Construction sequence in the analysis of barrel vaulted Romanesque churches

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Abstract

Major French Romanesque churches built during the late eleventh and early twelfth centuries often feature axially oriented masonry barrel vaults over central nave spaces. Nave side aisles and, when present, galleries are also usually vaulted. Construction sequences can play an important role in determining stresses and displacements for these churches. The feasibility of using an element "birth/death" capability to include the effects of the construction sequence in their finite element stress analysis is demonstrated. The potential importance of construction sequence effects is also demonstrated
Keywords: Romanesque, barrel vault, construction sequence, finite element analysis, stress, displacement, element "birth/death".

1 Introduction

Major French Romanesque churches built during the late eleventh and early twelfth centuries often feature thick axially oriented masonry barrel vaults over central nave spaces. Nave side aisles and, when present galleries, are typically covered by thick masonry groin, axial half-barrel (quadrant), or transverse barrel vaults.

Church construction took place in a sequential fashion. Lower levels were built before levels above them that they would ultimately support. Vaulting of the central space was almost invariably the last step in the construction sequence.

Deformations of the other portions of buildings due to self-weight occurred before this last step. Undeformed configurations for central vaults as they were erected included the effects of these deformations. Failure to reflect these effects can introduce undesirable error in finite element stress analysis of Romanesque churches with central barrel vaults.

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Finite element "birth/death" capability (ANSYS [1]), has previously been shown to make it possible to include the effects of construction sequence in the analysis of French Romanesque churches with unvaulted central spaces covered by timber framed roofs supported by transverse diaphragm arches (Van Gulick [2]). Extension of the consideration of construction sequence to the finite element analysis of French Romanesque churches with axially oriented central barrel vaults has now been carried out and potential effects on computed stresses for such buildings considered.

2 Abbey Church of St. Étienne at Nevers

The Romanesque Abbey Church of St. Étienne at Nevers, near the junction of the Allier and Loire Rivers in south-western Burgundy, was built in the second half of the eleventh century (Choisy [3], Anfray [4], Salet [5], Zenner [6, 7]).

The six-bay central nave of the church is covered by a rounded barrel vault reinforced by transverse arches at bay intersections, fig. 1. The five almost identical eastern nave bays are flanked by vaulted side aisles and galleries. The western, sixth, bay is structurally integrated with the two western towers above side aisle level. Its central space is spanned by a tribune at approximately gallery level.

The interior length of the nave, including the western bay, is approximately twenty-six meters. The width of its central space is approximately seven meters. Its total interior width, including side aisles, is approximately fifteen meters. The peak of the central vault is approximately eighteen meters above the floor. Dimensions presented here were obtained from published measured values [7] correlated with those obtained from scaled drawings [3, 4].

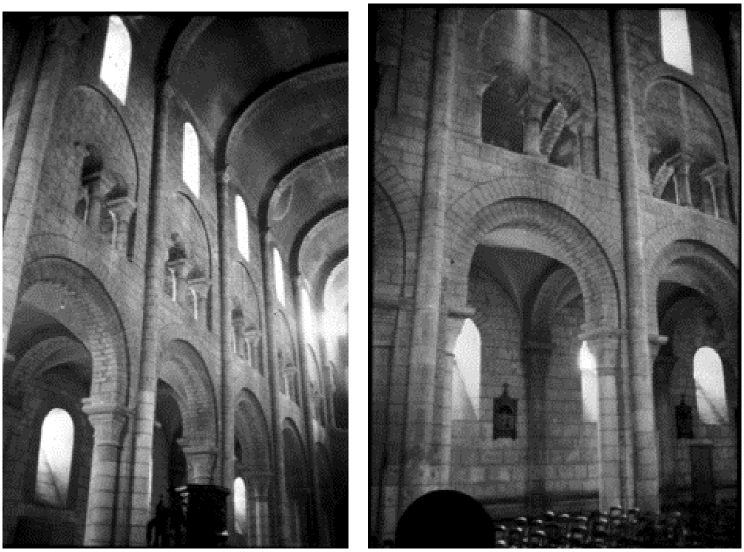

Figure 1: Nave of St. Étienne at Nevers.

Figure 2: Side aisle and gallery.

Figure 3: Gallery quadrant arches and vaults.

Side aisles are delineated from the central space by a nave arcade of circular arches rising from capitals above attached half columns. Round-headed windows in exterior walls allow direct lighting into side aisles and indirect lighting into the central nave. Thick side aisle groin vaults are reinforced by transverse ribs.

The transverse ribs, like the arches of the nave arcade, rise from capitals above attached half columns, fig. 2.

Galleries above the five eastern bays communicate with the central space through openings under paired arches supported by a central column and attached half columns, fig. 2. Columns and half columns rise from a balustrade slightly above gallery floor level. The paired arches are surmounted by recessed panels under relieving arches on both gallery and central nave sides. Galleries are covered by quadrant barrel vaults reinforced by quadrant arches resting at both ends on capitals above attached half columns, fig. 3.

Small windows under relieving arches in the outer wall allow a limited amount of direct lighting to enter the galleries, fig. 3. Little light from the gallery windows reaches the central nave space.

Direct lighting enters the central nave through clerestory windows, one per bay, located between the top of the gallery level and the springing of the central barrel vault. Transverse arches reinforcing the vault spring from capitals above attached half columns rising in an unbroken line from the floor, fig. 1.

The north wall of the nave exterior is shown in fig. 4. The south wall is similar, but is partially hidden from view by remains of the abbey cloister. The exterior wall of the nave and side aisle is seen to present a smooth unbroken surface except for recessed panels surrounding the five side aisle windows that extend down to just above ground level. The recessed panels are set below shallow relieving arches and are separated by wide shallow pilaster strips.

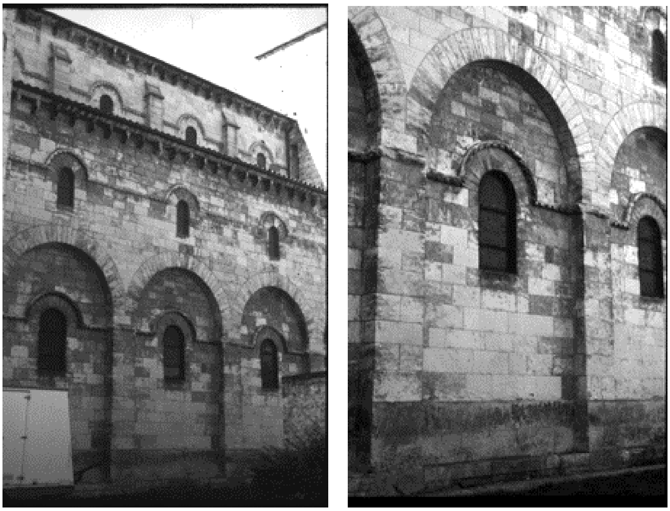

Figure 4: Exterior north nave wall.

No external buttresses reinforce the nave side aisle and gallery exterior wall. The clerestory exterior wall, on the other hand, is reinforced by four substantial wall buttresses. Buttress axial locations correlate with divisions between bays and hence correlate with locations of central vault transverse ribs and gallery quadrant arches.

Finite element analysis of a typical eastern nave bay of St. Étienne was carried out to investigate the effects of construction sequence in the analysis of centrally barrel-vaulted French Romanesque churches.

3 Analysis

The analysis was carried out using general-purpose finite element code ANSYS Release 10.0 (ANSYS [8]). Ten-node SOLID92 tetrahedral elements with quadratic displacement functions were used because they are particularly well-suited for analyzing the complex three-dimensional geometry typical of French Romanesque churches [2].

Based on axial and transverse symmetry conditions under dead weight, i.e. gravity loading, a solid model of one quarter of a typical bay of the building was employed. A solid model previously constructed for a Lafayette College Senior Honors Project, Stenman [9], was modified by subdividing it into five volumes to facilitate selecting associated elements for birth and death operations. The five volumes consisted of the side aisle and gallery levels, clerestory level, central transverse arch, and central barrel vault, fig. 5.

The associated finite element model contains 95,417 nodes and 58,635 elements, fig. 5. Nodes at ground level were fixed in all degrees of freedom and appropriate symmetry displacement degrees of freedom and inertial gravity loading applied.

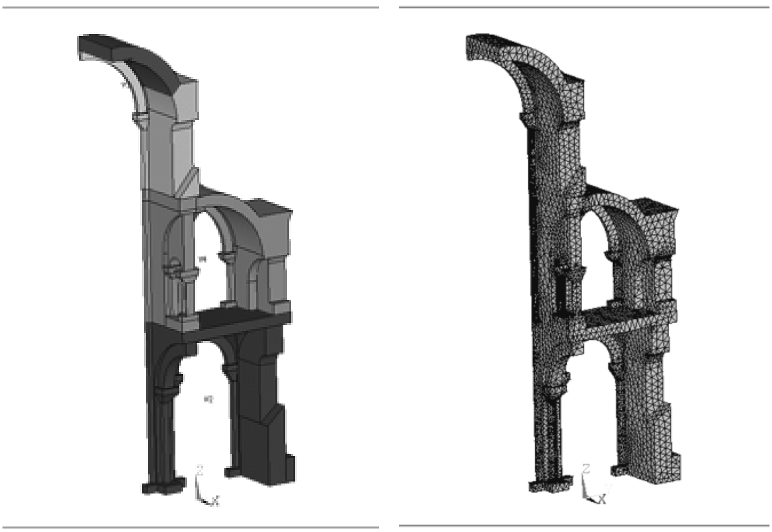

Figure 5: Finite element volumes and elements.

Stresses were first computed without considering construction sequence, i.e. with a one-step sequence. They were then computed using a five-step construction sequence beginning at the side aisle level and proceeding upward through the gallery level, clerestory level, transverse arch, and central vault volumes. Elements associated with a volume being added were “born” stress-free at that stage in the computational process.

Computed first principal, that is tensile stresses, for the one-step and five-step sequence analyses are compared in figs. 6 through 9. Stress contour levels were chosen so that only stresses above the nominal 200 kPa cracking level for medieval mortar are shown. Stresses computed with the one-step sequence are shown to the left on the figures, stresses computed with the five-step sequence to the right.

In all cases, tensile stresses are only present in limited local areas of the building. This is to be expected for a well-constructed medieval building that has survived for over nine-hundred years.

Relatively low level, less than 400 kPa., computed tensile stresses in the side aisle vaults near the transverse ribs, accompanied by somewhat higher stresses in a limited region of the ribs, were obtained for both one-step and five-step analyses, fig. 6. Computed stresses are somewhat lower and occur in a smaller area for the five-step analysis.

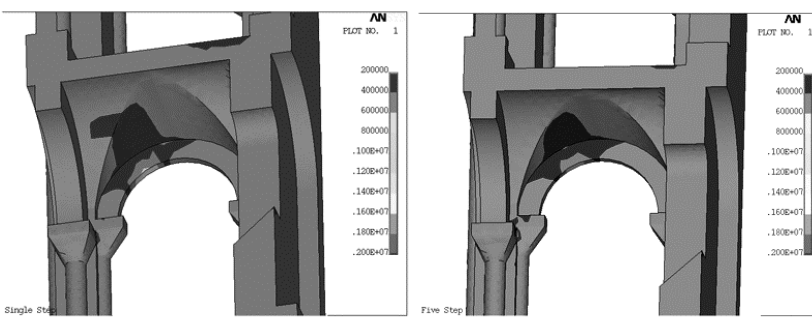

Figure 6: Tensile stress: side aisle vault and transverse rib.

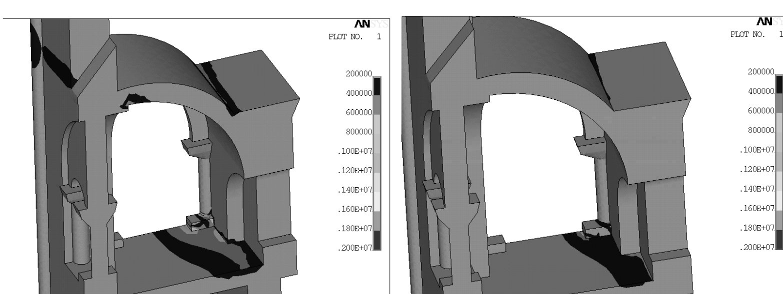

Figure 7: Tensile stress: gallery floor.

Similar results are observed for gallery floor stresses, fig. 7. Tensile stresses computed for the one-step sequence cover approximately the outer third of the floor. They range up to 600 kPa, except near sharp edges, where they are higher. Stresses computed with the five-step sequence cover approximately the outer quarter of the floor and generally do not exceed 400 kPa.

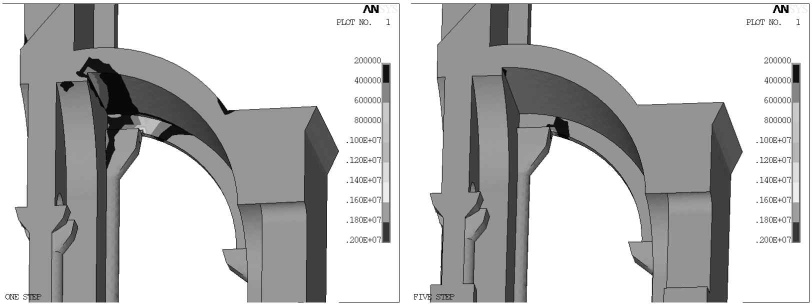

Figure 8: Tensile stress: gallery vault and quadrant arch.

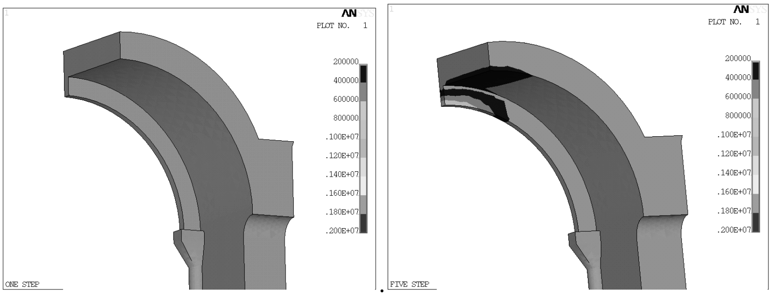

Figure 9: Tensile stress: central barrel vault and transverse arch.

Tensile stresses of less than 400 kPa were obtained in limited areas of the central nave clerestory wall and outer upper gallery vault surface for the one-step sequence, fig. 7. Tensile stresses were much reduced or eliminated in these regions for the five step sequence.

Computed gallery vault tensile stresses of up to between 600 to 800 kPa for the one-step sequence are seen in fig. 8. They are accompanied by similar stresses in the quadrant arch reinforcing the vault. The extremely high, very localized, stresses computed near the arch/capital intersection are due to physically unrealistic discontinuity effects present in the analysis.

Tensile stresses in the gallery vault are eliminated when a five step sequence is considered, fig. 8. Stresses in the gallery quadrant arch are similarly eliminated, except near the arch/capital intersection.

No tensile stresses were computed in the central nave barrel vault or transverse arch when a one-step sequence was employed, fig. 9. Low level tensile stresses, less than 400 kPa, appeared in the inner portion of the lower central vault surface for the five-step analysis.

Stresses also appeared in a portion of the transverse arch for the five-step analysis. The relatively high levels, up to 800 kPa, of stress observed there are due to the physically unrealistic assumption of shear continuity between the arch and the vault above it. In reality, relative sliding would almost certainly take place. The arch and vault would behave as contacting bending members with individual cross sections. Including this phenomenon in the analysis would have required the use of contact surfaces between the arch and vault. Future studies will pursue this option.

Consideration of computed deformations facilitates physical understanding of the observed effects of construction sequence on computed stresses.

As the side aisle, gallery, and clerestory levels are constructed, significantly greater vertical displacements occur in the nave arcade piers and inner gallery wall than in outer side aisle and gallery walls. As a result, the building tends to rotate inward. For the one-step analysis, the central barrel vault and transverse arch oppose this rotation, exerting a large outward horizontal force on the upper clerestory wall. An equal, but opposite inward horizontal force is exerted on the vault and arch. For the five-step analysis, the central barrel vault is not present during initial stages of construction. Rotation is unopposed, and the above horizontal forces do not occur.

Higher tensile stresses computed in side aisle vaults and ribs, gallery floor, and particularly gallery vaults and quadrant arches by the one-step analysis are due to the outward horizontal force exerted by the central arch and vault. The accompanying inward force generates compressive stresses in the central arch and vault, negating tensile stresses resulting from their bending under self weight. Tensile stresses are observed in the central arch and vault in the results of the five-step analysis due to the absence of these compressive stresses.

4 Conclusions

The feasibility of using element “birth/death” capability to incorporate the effects of construction sequence in the finite element stress analysis of typical centrally vaulted French Romanesque churches has been demonstrated. The potential importance of such effects has also been demonstrated.

This study has considered only linear elastic material behaviour. Even more significant construction sequence effects are to be expected when nonlinear or time dependent phenomena such as cracking, creep or foundation settlement are considered.

The study has assumed rigid connections between all contacting structural components. In actuality, relative sliding may occur between some components, vaults being erected on previously constructed arches or ribs, for example.

Future studies investigating nonlinear and time dependent material behaviour and relative sliding between structural components, in combination with construction sequence, are planned.

References

[1] ANSYS, *ANSYS Advanced Analysis Techniques Guide: ANSYS Release 10.0,* ANSYS, Inc., Cannonsburg, pp. 13-1-13-6, 2005.
[2] Van Gulick, L.A., Construction sequence in the finite element analysis of Romanesque churches, *Structural Analysis of Historical Constructions,* eds. C. Modena, P.B. Lourenço, & P. Roca, Taylor & Francis Group, London, pp.635-641, 2005.
[3] Choisy, A., Histoire de L'Architecture, Slatkine Reprints, Genève-Paris, Tome 2, pp. 210-212, 1987.
[4] Anfray, H., L'Architecture Religieuse du Nivernais au Moyen Age: Les Églises Romanes, Ëditions S. et J. Picard, Paris, pp. 37-61, 1951.
[5] Salet, F., Saint-Étienne de Nevers, *Congrès archéoligique de France, CXXVe session, 1967, Nivernais*, Société française d'archéologie, pp.162-184, 1967.
[6] Zenner, M.T., *Saint-Étienne de Nevers*, Camosine: Les Annales des Pays Nivernais, Nevers, 1995.
[7] Zenner, M.T., *Methods and Meaning of Physical Analysis in Romanesque Architecture: A Case Study, Saint-Étienne in Nevers (France),* Dissertation, Bryn Mawr College, Bryn Mawr, 1994, UMI, 1994.
[8] ANSYS, *ANSYS Structural Analysis Guide: ANSYS Release 10.0,* ANSYS, Inc., Cannonsburg, 2005.
[9] Stenman, C.A., *Structural Analysis and Design: The Nave of the Abbey Church of St. Etienne at Nevers,* Thesis, Lafayette College, Easton, 2003.