Aircraft Impact Analysis of New York World Trade Center Tower by Using the ASI-Gauss Technique

D. Isobe[1] and K. M. Lynn[2]

Summary

In this paper, a newly developed ASI-Gauss technique is applied to an aircraft impact analysis of New York World Trade Center Tower 2 (WTC2), to evaluate the structural vulnerability and behavior of the aircraft, at the horrifying scene that occurred in 2001. The ASI-Gauss technique is a modified version of the formerly developed Adaptively Shifted Integration (ASI) technique for the linear Timoshenko beam element, which computes highly accurate elasto-plastic solutions even with the minimum number of elements per member. Algorithms considering member fracture and elemental contact are also implemented. The analytical results such as damages of the tower and motion of the aircraft engines, showed good agreement with the observed data.

Introduction

The aircraft impact and progressive collapse of the World Trade Center (WTC) towers, an unprecedented building disaster, pointed out that peculiar external loads and phenomena, which are not considered in building designs and about which little technical information is available, can lead to the total collapse of buildings and the loss of many lives. It may be impractical to adopt building codes that demand structural capabilities to resist such loads and phenomena. However, we should have in-depth technical knowledge about them in order to minimize fatalities and structural damage. Due to the nature of the problem, finite element simulation with dynamic schemes and global analytical models is considered to be an effective means of clarifying actual phenomena. However, conducting dynamic analyses of full-model large-scale structures such as the WTC towers leads to high calculation cost, and it usually becomes a bottleneck. If the analyzed phenomenon is a lengthy one, such as the fire-induced collapse of a large-scale structure, the problem of calculation cost becomes more significant.

To fulfill the desire to reduce calculation costs, a new scheme called the ASI-Gauss technique, which can effectively cope with strong nonlinearities and discontinuities common in impact collapse problems, is developed. In this paper, the newly developed ASI-Gauss technique is briefly explained, and it is compared with the former version of the technique, the Adaptively Shifted Integration (ASI) technique [1] for the linear Timoshenko beam element. Algorithms considering member fracture and elemental contact [2] are also implemented. An impact collapse analysis is conducted using a

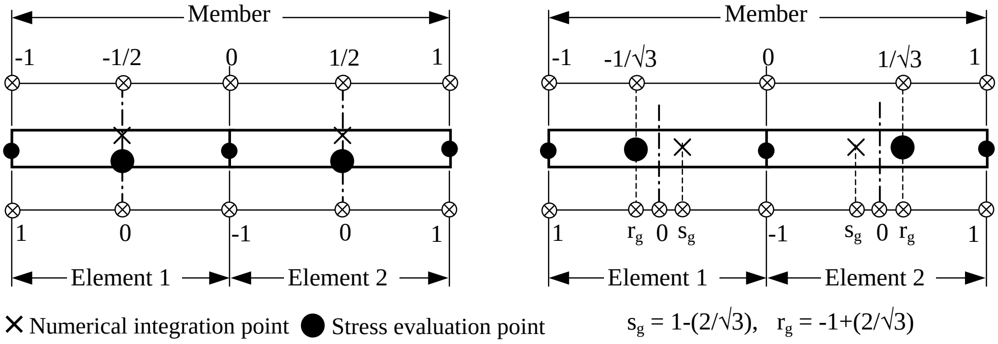
---

[1] Department of Engineering Mechanics and Energy, University of Tsukuba, Ibaraki 305-8573, Japan
[2] Ex-graduate student, University of Tsukuba, Ibaraki 305-8573, Japan

detailed finite element model to simulate the aircraft impact with the World Trade Center South Tower (WTC2), and the analytical results are compared with the observed data.

ASI-Gauss Technique

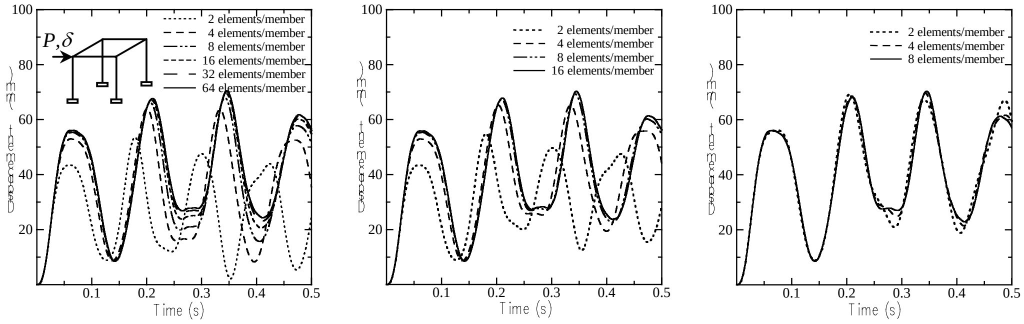
The main difference between the ASI and ASI-Gauss techniques lies in the position of the numerical integration point in elastic range. In the ASI-Gauss technique, two consecutive elements forming a member are considered as a subset, and the numerical integration points of an elastically deformed member are placed such that the stress evaluation points coincide with the Gaussian integration points of the member. This means that stresses and strains are evaluated at the Gaussian integration points of elastically deformed members. Gaussian integration points are known to be optimal for two-point integration and the accuracy of bending deformation is mathematically guaranteed. In this way, the ASI-Gauss technique takes advantage of two-point integration while using one-point integration in actual calculations. Figure 1 shows the locations of the numerical integrations points of elastically deformed elements in the ASI and ASI-Gauss techniques.



(a) ASI technique **(b) ASI-Gauss technique**

Fig. 1 Locations of numerical integration and stress evaluation points in elastic range

An Elasto-plastic response analysis is performed to evaluate the convergency of the schemes. A load of 12 kN is applied to a space frame as shown in Fig.2. The conventional scheme shows a very slow convergence and sixteen-element modeling is necessary to obtain the converged solution. Although the ASI technique gives comparatively better results than the conventional scheme, a difference in the vibration mode can be observed in less-element modeling. On the other hand, the ASI-Gauss technique shows a very fast convergence and nearly converged solutions are obtained even when the number of elements per member is two.

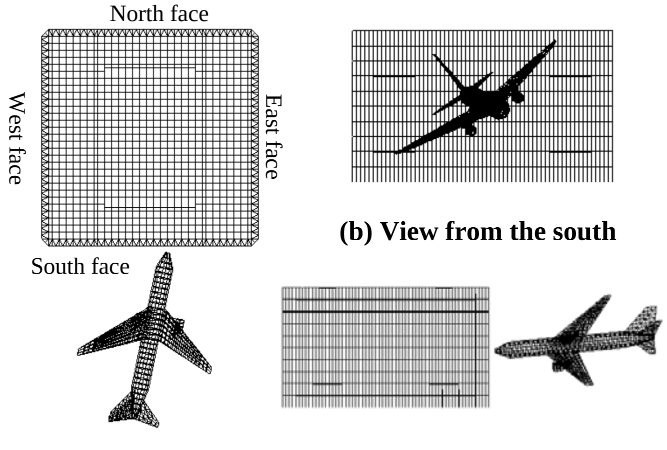


(a) Conventional scheme **(b) ASI technique** **(c) ASI-Gauss technique**

Fig. 2 Elasto-plastic responses of space frame

Aircraft Impact Analysis of World Trade Center Tower 2

An aircraft impact analysis of WTC2 is carried out by using the ASI-Gauss technique. Figure 3 shows the analytical finite element model and the initial position of the aircraft. The floors near the region of aircraft impact, 77th to 86th floor, are modeled with linear Timoshenko beam elements. The number of elements per member is uniformly set to two. The analytical model contains 54740 elements, 47267 nodes and 281880 degrees of freedom. The boundary conditions for the upper and lower ends are assumed to be horizontal rollers. Two parameters used for fracture criterion, axial and bending strains, are set to 0.1 and 0.0003 respectively, for perimeter and core columns. The mean weight per unit floor area is assumed to be 8.29 kN/m^2. The initial gravity load is applied to all structural members. A B767-200ER aircraft is also modeled with linear Timoshenko



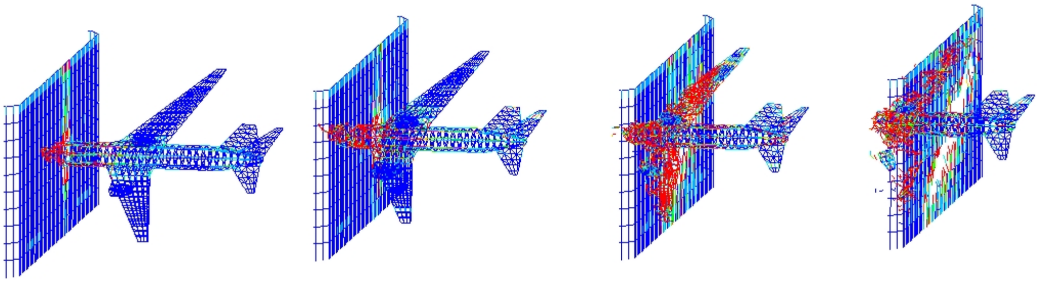
(b) View from the south

(a) Aerial view **(c) View from the west**

Fig. 3 Analyzed model and initial position of aircraft

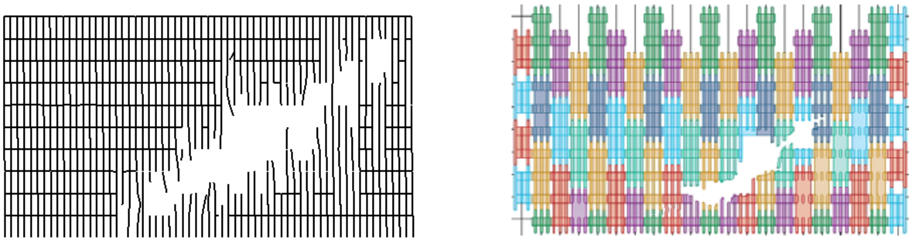
beam elements. The model consists of 4322 linear Timoshenko beam elements, 2970 nodes and 17820 degrees of freedom. The two-element modeling is also used. All structural members of the aircraft are assumed to have box-shaped cross sections and the material properties of extra super duralumin. The total mass of the aircraft at the time of impact is assumed to be 142.5 t, which is the sum of the masses of the aircraft (112.5 t) and the jet fuel (30 t). The mass of each engine is 19.315 t. The nose of the aircraft is tilted 11.5 degrees to the east and 5 degrees downward, and its left wing is inclined downward by 35 degrees. It is assumed to collide with the 81st floor of WTC2 with a cruise speed of 590 mph (262 m/s) [3]. Newmark’s β method (δ=5/6, β= 4/9) [4], updated Lagrangian formulation and the conjugate gradient (CG) method is used in the analysis. The analytical code is run on a personal computer (3.3 GHz P4 CPU and 2GB RAM), and the calculation takes approximately 23 hr for a physical time of 0.8 s.

Figure 4 shows how the aircraft cuts through the perimeter columns and spandrels on the south face. Fractured elements are not plotted in the figures. Immediately after the impact, shock waves travel up and down in the perimeter columns and back and forth in the longitudinal members of the fuselage. The engines are detached from the aircraft soon after the main wings crashed into the south face. Figure 5 shows the damages of the perimeter columns and spandrels on the south face. The result obtained from the analysis is slightly larger than the observed one [3] especially near the lower and upper boundaries, where horizontal rollers are assumed. Due to these boundary conditions, it is assumed



(a) 0.04s **(b) 0.08s** **(c) 0.12s** **(d) 0.16s**

Fig. 4 Aircraft cutting through perimeter columns and spandrels on the south face

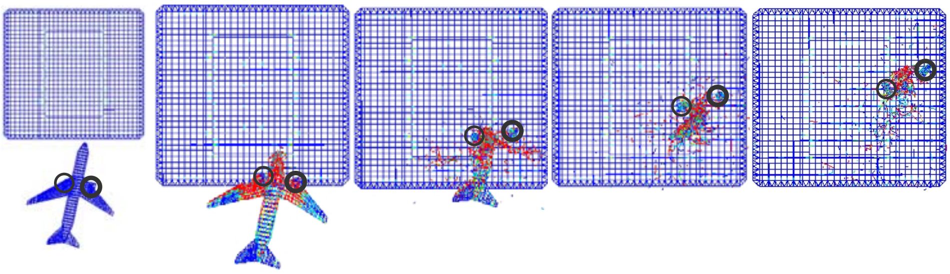


(a) Analysis **(b) Observed damage [3]**

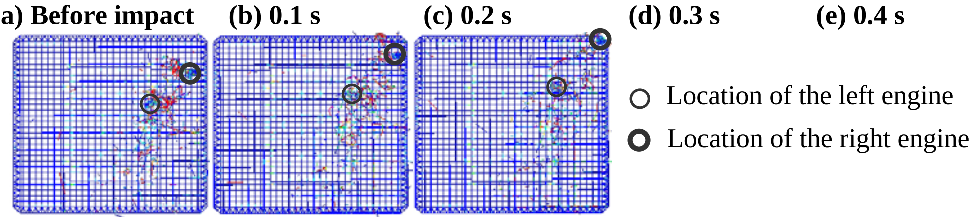
Fig. 5 Damages on the south face

that stresses are totally reflected from these boundaries, and the elements near them became severely stressed.

Figure 6 shows how the aircraft debris moves through the building and to where it causes damage. As shown in the figure, the right engine does not cause damage to the core structure. It moves out from the northeast corner at 0.7 s (0.617 s after the impact). The location from where the right engine moves out of the building is almost the same as the observed data [3]. The core structure is mainly damaged by the left engine and fuselage. The debris of the fuselage moves out from the north face. The velocity of the left engine is reduced more than that of the right one since the left one collides with the members of the core structure. Figure 7 shows the velocity reduction curve of the right engine, which is in very good agreement with the observed data [3]. The right engine moves in the northeast direction after coming out of the building at a velocity approximately of 53 m/s. Its traveled distance after moving out of the building is calculated to be 368 m. The engine was reported to have been found at the corner of Murray and Church Streets [3], which is approximately 443 m far from the building. Therefore, the analytical result is in good agreement with the observed data if we take into account that the engine rolled over after reaching the ground.



(a) Before impact **(b) 0.1 s** **(c) 0.2 s** **(d) 0.3 s** **(e) 0.4 s**



(f) 0.5 s **(g) 0.6 s** **(h) 0.7 s**

Fig. 6 Motion of aircraft debris during impact

Conclusion

In this paper, we briefly discussed on the newly proposed ASI-Gauss technique for the linear Timoshenko beam element, which takes advantages of two-point integration

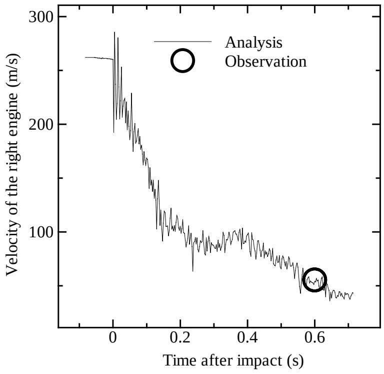


Fig. 7 Velocity reduction curve of the right engine

while using one-point integration in actual calculations. The scheme is used to analyze dynamic collapse behavior of WTC2 subjected to aircraft impact, and the propagation of shock waves resulting from the impact is confirmed. The damages of the tower and motion of the aircraft engines are practically in good agreement with the observed data. However, there still lie inconveniencies due to the usage of partial models. Therefore, a full-model analysis of WTC2 is scheduled to estimate the influence of shock waves generated by the aircraft impact, against the progressive collapse of the tower that occurred 56 minutes after the impact.

Acknowledgement

This work is partially supported by Grant-in-Aid for Scientific Research No.16206055, Japan Society for the Promotion of Science.

Reference

1 Toi, Y. and Isobe, D. (1993): "Adaptively Shifted Integration Technique for Finite Element Collapse Analysis of Framed Structures", *International Journal for Numerical Methods in Engineering*, Vol. 36, pp. 2323-2339.

2 Isobe, D. and Tsuda, M. (2003): "Seismic Collapse Analysis of Reinforced Concrete Framed Structures Using the Finite Element Method", *Earthquake Engineering and Structural Dynamics*, Vol. 32, No. 13, pp. 2027-2046.

3 ASCE/FEMA (2002): *World Trade Center building performance study: Data collection, preliminary observation, and recommendations.*

4 Bathe, K. J. (1996): *Finite element procedures*, Prentice Hall.