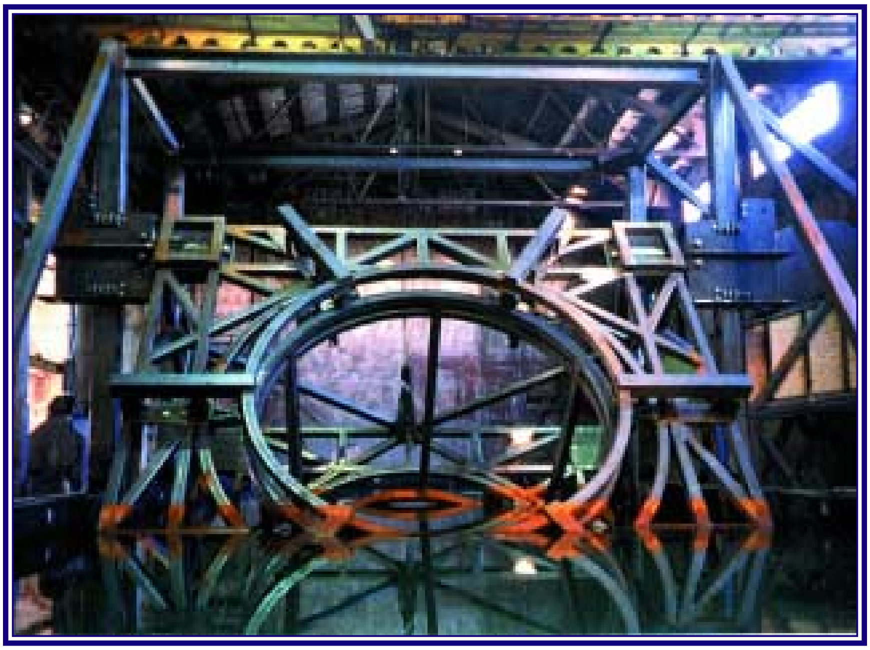
# THE STRUCTURE OF A HOLLYWOOD PLANE CRASH

## Specially designed steel gimbals were critical to the fabulous special effects in the movie *U.S. Marshals*



*Pictured at top is the rotating gimbal during the water tank test. Shown above is the gimbal with the airplane fuselage installed.*

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DIGITALLY ENHANCED MOVIES ARE GETTING ALL THE PRESS – think Antz, A Bug's Life, Armageddon, Godzilla, Jurassic Park: The Lost World, Titantic, Toy Story… It seems like Silicon Valley is trying to make Hollywood redundant. So it is refreshing to see that some action films are still made the old-fashioned way – build a set, add actors and shake well! Thornton-Tomasetti Engineers (TT) had the pleasure of helping such a production, U.S. Marshals, a Warner Bros. film released March 1998. This sequel to The Fugitive features an extended airplane crash sequence as a critical plot device. For a realistic, detailed crash on a reasonable budget, the producers decided to use full-scale sets, filming in a Chicago warehouse-turned-soundstage and on location on the Ohio River. TT's contribution was the structural design of several devices to tilt, jostle, flip and sink actual airplane fuselages with actors inside.

The scene: During a prisoner transport flight, a shot from a smuggled gun results in sudden depressurization and damage of the fuselage. The plane goes into a turbulent dive. An emergency landing is attempted on a straight roadway which takes a sudden turn, sending the plane into the Ohio River upside-down. Marshals race to evacuate the prisoners shackled to their seats as the sinking plane fills with water. The last person to leave the plane before the cabin goes completely under water is Marshal Sam Gerard (Tommy Lee Jones).

Much of the footage for this scene required the use of full aircraft sets. The decision was made early to obtain and use two full Boeing 727-200 fuselages for the filming. Gimbals, motion-control structures common to the special effects industry, were necessary to tilt, rock, roll, and submerge these fuselages. One fuselage was fitted to two different gimbals in sequence for the interior footage. A third gimbal was required to float and manipulate the second fuselage on the Ohio River for the exterior shots.

Warner Bros. first contacted TT to investigate the feasibility of building a 300,000-gallon tank in the floor of the studio building, to submerge an airplane fuselage. As this was the last industrial building designed by Daniel Burnham, it was important not to damage or alter its basic fabric. After evaluating the building and determining that the water tank could be installed, TT was selected to provide design, detailing and construction coordination services for the three gimbals.

### Rocking Gimbal

The first gimbal simulated the turbulent descent and rough landing of the aircraft, as seen from the passenger cabin. It tilted the 50,000-pound, 86'-long partial fuselage from level to fifteen degrees with the tail up. At the same time, the gimbal was required to rock the fuselage and its 65 occupants up to five degrees to each side. The primary constraint affecting this gimbal's design and operation inside the building was the need to achieve a steep angle of inclination without interfering with roof trusses 30' above the floor.

This structure consisted of three tube-steel platforms. The upper platform, attached to the fuselage along five circumferential ribs, depended on the fuselage for its lateral stability. This platform rested on high-strength elastomeric airbags like those used as the axle springs in trailer and truck suspensions. The airbags generated up to 10,000 pounds of force when inflated, and reacted against the middle platform, which was hinged at one end and supported by two large, high-capacity hydraulic cylinders at the other. The large hinges were designed to resist the high lateral and inertial

*Pictured at top is a view of the inside of the fuselage. Shown above is a view of the tail end where the hydraulic cylinder connects the lower and middle platforms.*

forces generated while the airbags rocked the set above. To provide the great capacity required, the hinges were constructed of high strength, low alloy steel and mechanical tubing. To span the 65’ distance between the hinge and the cylinders, this platform was designed with two 6’ deep trusses, one on each side of the fuselage.

Steel buttresses kept the upper platform from sliding off the middle platform when rocking the fuselage in the inclined position. High-strength plastic bearing pads were installed on the sides of the platform and on each buttress to allow smooth motion when the two were in contact. The base platform was the main reaction frame. It transferred and distributed all the loads to the warehouse floor without any additional foundations. A grid of tubular steel members on 1/2” steel plates was assembled. The entire grid was then filled with concrete to resist uplift forces and to dampen the dynamic forces from the platforms above. The other side of the hinge was built into this platform, as were the hydraulic cylinder mounts.

The total weight of the dynamic system was 150,000 pounds. The overall geometry of the platforms and the hydraulic cylinders left about one foot of clearance for the tail end of the fuselage to fit between roof trusses when raised to the full fifteen-degree tilt while rocking the fuselage.

### Rotating Gimbal

The second gimbal simulated the aircraft skidding out of control, rolling down the riverbank and sinking, again as seen from the passenger cabin. The actors and stunt personnel were strapped to their seats while the fuselage was rolled 180 degrees and lowered into a water tank. This gimbal was designed to operate anywhere from level, upright, and above the water’s surface to inclined, upside-down, and completely submerged. This required a sophisticated design and precise fabrication to handle simultaneous rotations about two axes and translation along the third axis. To accomplish this, the second gimbal set had four main elements.

First, exterior rings of tubular steel and plate fastened to the fuselage at wing anchor points provided a smooth, round 'race' for the 'roll-over' bearings, making the fuselage a giant axle. Because the fuselage was also being used for earlier scenes in the Rocking Gimbal, the rings had to allow for last-minute installation of the plane with about four inches of overall clearance. Only the center of the plane was held; both ends of the fuselage protruded beyond the bearings as self-supporting cantilevers.

Second, the bearing itself was a series of heavy steel wheels, 10" in diameter, mounted directly to a space frame which could be lifted and tilted. The fuselage was rolled by four hydraulic motors driving rubber tires pressed against the races on the fuselage. To keep the fuselage from wandering out of the space frame while rotating and tilting, additional wheels were used to keep it centered.

Third, an outer stationary space frame spanned over the water tank to guide the inner moving space frame/bearing and provide reaction points for the four hydraulic cylinders which supported and manipulated it. Four 14" square steel tubes were used as columns, and wide-flange shapes and tubes were used as beams and bracing. Two vertically fixed cylinders carried the majority of the loads, bearing on the foundations of the tube steel columns. Each cylinder moved a steel-plate carrier along 12' of vertical travel, guided on the square columns by a set of 20 4" roller bearings. A pivoting block inside each carrier supported a large diameter, high strength, low alloy steel trunnion projecting from the upper front corner of the inner space frame at the center of gravity of the combined fuselage and space-frame assembly. These secondary pivots allowed for differential extension between the two main hydraulic cylinders which otherwise would have racked and damaged the inner space frame, freezing the fuselage in its roll. As a result the inner space frame could tolerate 10 degrees of misalignment at any position without impeding the axes of pivot and roll. The other two cylinders were attached to the lower back end of the inner space frame and hung from the top of the outer space frame. They were used to adjust the overall inclination of the

*Shown above is the floating gimbal being assembled for transport to the Ohio River site. Visible are longitudinal pipes, transverse trusses and fuselage connections.*

inner space frame and fuselage from 5-degrees diving to 15-degrees ascending. The trunnions, bearing shells and pivot blocks were all fabricated, welded and machined to within 0.0030", a tolerance that allowed all assemblies to rotate and pivot without binding.

The fourth important element was the water tank, the key to this scene. The water tank was 30' wide, 105' long and 18' deep. A pit was excavated using steel piles and wood lagging. A concrete pool was then built inside the lagging, and the fixed space frame was constructed over the tank.

To provide the required range of motion and the ability to submerge the fuselage without interference from the building envelope, detailed site surveying and computer modeling were used to study the interaction of the tank, fuselage and site. In addition to the high dynamic loads caused by the rolling and moving fuselage, hydrodynamic load conditions were also considered: the capacity to rapidly lift the fuselage from the 'dunked' position was important for the actors' safety. The total dry weight of the moving structures was 150,000 pounds, and wet design load was 180,000 pounds.

## Floating Gimbal

The third gimbal was necessary for the crash scene at the Ohio River, in southern Illinois. A full-length, 125' long, 40,000-pound Boeing 727 fuselage was to be held above the water's surface and manipulated as it gradually sank.

A submersible space truss raft with pivoting airplane support was designed for this purpose. Six tube trusses connected three steel pipes, each 2' in diameter, 105' long and subdivided into five ballast sections which could be independently flooded with water or purged with air. These tanks allowed the special effects crews to not only control the rate but also the angle of the gimbal's submersion. As the gimbal sank, the inverted fuselage slipped into the murky waters of the river. In addition to the ballast system, a hydraulic cylinder was used as the forward connection of the fuselage to the raft to provide additional fine-tuning of the fuselage's inclination.

Internal steel framing was also designed for the fuselage. First, all forces had to be transferred from the fuselage to the raft, while allowing for a modest amount of rotation about a crosswise pivot. Second, the entire system had to be lifted out of the water as one unit, using only two lifting points at the top of the inverted fuselage. Third, support had to be provided for an internal "dump" tank, designed to hold over 250 cubic feet of water which could be released on cue during filming. As this gimbal was to be fabricated in Chicago and filmed in Kentucky, it was designed for easy disassembly and transportation. The fuselage and trusses separated into halves, and each pipe separated into three sections. It was shipped by barge to the film site via the Mississippi River.

Concrete deadmen placed on the riverbed served as anchors for a system of pulleys that directed steel cables connected to winches on land. These cables and winches provided additional control of the gimbal's position while submerged. To keep the gimbal/plane assembly from sinking in event of a pump failure, large closed-cell foam blocks were installed within the cargo bay of the fuselage, adding 50,000 pounds of buoyancy to the 90,000 pounds provided by the raft. The overall width of the raft was limited to 20', to ensure that actors jumping from the 12' wide fuselage during the night-time filming did not injure themselves on the submerged structure.

## Successful Fabrication

Despite demanding cinematographic requirements and an extraordinarily short 12-week fabrication schedule, the three gimbals were designed and fabricated successfully, and to a degree of precision uncommon in the general construction industry. This success was due in large part to cooperation between members of the design and fabrication teams. The fabricator's skilled and knowledgeable staff was essential to providing high precision fabricated assemblies which performed without fault.

## Conclusion

Each of the gimbals required significant analysis of large, complex structures subjected to high accelerations and dynamic loads. At the same time, rapid design and detailing services were required to finish the project on schedule. All of the gimbals were designed with the innovative use of ordinary structural materials: structural steel plate, rolled shapes and tubular shapes, high strength alloys, non-ferrous alloys, aluminum, plastics, epoxies and readily available components with a minimum of specialized parts. A tremendous amount of coordination was required between the structural system and the other engineered systems, specifically hydraulics and pneumatics. Machined parts with small tolerances and critical alignments were required for each of the gimbals to function. This combination of type, scale, and materials is not often seen together in commercial and residential structural engineering projects.

The gimbals provided several groundbreaking departures from previous Hollywood gimbal designs: No rocking gimbal had ever been built to rock in an inclined position, and no rolling gimbal had ever been designed to operate in a tank of water. These departures were significant to the special effects department for two reasons. First, the new designs enabled more realistic footage than previously achieved. Second, conventional effects teams must create innovative designs on every project to remain competitive with computer graphic effects companies.

In addition, the design and fabrication of the three Gimbals represented a first for the City of Chicago. Nothing of this type, size, or construction had ever been designed and built in Chicago for the motion picture industry. Special effects are usually designed and constructed in Hollywood studio lots. The cinematographic success of the gimbals created a wonderfully realistic scene for the movie. The economic and injury-free success of the gimbals furthers Chicago's reputation as a viable location for the filming of Hollywood's most vigorous and exciting movies.

Only time will tell whether computer graphics will further encroach on the realm of conventional special effects. But it is satisfying to see that at least some filmmakers are still using more traditional techniques with stunning results. If only we could see a return to old-fashioned ticket prices!

*Thornton-Tomasetti Engineers is a consulting structural engineering firm providing design and investigation services on a worldwide basis, from offices in New York, NY, Chicago, IL, Trumbull, CT, Dallas, TX, Newark, NJ, and San Jose, CA. Joe Burns is a Principal in Thornton Tomasetti Engineers' Chicago office. (phone: 312/346-0190; email at jburns@ttchicago.com). Dennis Pantazis is a Senior Engineer in Thornton Tomasetti Engineers' Chicago office (phone: 312/346-0190; email: dpantazis@ttchicago.com). Jonathan Block is a Senior Engineer in Thornton Tomasetti Engineers' Chicago office (phone: 312/346-0190; email: jblock@ttchicago.com. Len Joseph is a Principal in Thornton Tomasetti Engineers' New York office (phone: 212/924-9400; email at ljoseph@ttengineers.com).*