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Vertical Picture-Frame Wing Jig Structure Design with an Eye to Foundation Loading

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Michael Carr
Electroimpact Inc

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ABSTRACT

The foundation of many production aircraft assembly facilities is a more dynamic and unpredictable quantity than we would sometimes care to admit. Any tooling structures constructed on these floors, no matter how thoroughly analyzed or well understood, are at the mercy of settling and shifting concrete, which can cause very lengthy and costly periodic recertification and adjustment procedures.

It is with this in mind, then, that we explore the design possibilities for one such structure to be built in Belfast, North Ireland for the assembly of the Shorts C-Series aircraft wings. We evaluate the peak floor pressure, weight, gravity deflection, drilling deflection, and thermal deflection of four promising structures and discover that carefully designed pivot points and tension members can offer significant benefits in some areas. However, when taken as a whole, a structure with moment-supporting corners and thermally independent upper and lower beams outperforms the other designs considered.

INTRODUCTION

Electroimpact has a history of delivering innovative, first-class automation and manufacturing solutions in the aerospace industry. Each project is an opportunity to execute, learn from, and advance the state of the art. So, when called on to design and build a new set of picture-frame jigs for the Shorts C-Series wings in Belfast, North Ireland, the first step was to reflect on past projects and identify the challenges we would be facing in the development of the major structure.

The list was not short. This structure would form the frame that all other tooling would depend on for accuracy and rigidity. The requirements were daunting, and there would be no tolerance for failure. But one challenge stood out above the rest: foundation movement.

We know from past experience that foundations do move and that this can be a serious problem for the precision structures that rely on them. Concrete has a tendency to shift and settle, seemingly of its own volition. It can move a great deal as it cures in the months (and years) after it is first poured, it can creep under load, and it can swell with changes in temperature. Understanding fully the mechanics of what is happening beneath our jig is far beyond the scope of this paper, but we must acknowledge that the beast is there, and do what we can to mitigate its causes and minimize its effects.

There are a multitude of other challenges in the design of a precision jig structure for the exacting environment of aircraft manufacture, but the foundation is singled out because we are utterly dependant on it to be successful, yet it is all too easy to overlook during our analysis of structural steel. As we carefully balance deflection, weight, and resonance against cost and manufacturability, we cannot ignore the floor that will support our steel. That one factor can easily render even the most elegant design miserably unfit for use unless it is given the consideration it deserves. In the following text, we will look beyond typical structural steel analysis and explore several possible causes of foundation movement and what can be done to mitigate them. Only then do we have any hope of seeing our steel jig behave in the real world as it does on our computer screens.

BACKGROUND

In the year before work began on this project, a team of Electroimpact engineers completed the installation and handover of a very similar structure to the same customer. This was a vertical picture-frame jig for the C-Series demonstrator wing box (figure 1) in a factory just down the street from the new building site. Though there are some critical differences, the data collected during the establishment of this demonstrator wing box jig highlighted the problem quite clearly.

Figure 1. C-Series Demonstrator Wing Box Jig, Belfast

Hundreds of data points collected over three months illuminated three key contributors to foundation movement. First, we observed a change over time, with the largest movement occurring during the first month after jig construction, and leveling out as the concrete cured. Second, there was a noticeable shifting of the floor due to uneven heating of the jig upper beam. Finally, and most significantly, we saw a very large movement immediately under the outboard corner of the inboard tower, as well as a smaller movement under the inboard corner of the outboard tower.

The first issue can only be properly mitigated through improved foundation design, and even still can probably never be truly eliminated. The foundation settling trend was measured fairly uniformly across the length of the jig, meaning that the forces from the jig itself were not a significant factor. Fortunately, the foundation for the new factory will be more robust than the one on which the demonstrator wing box jig was built.

The second point must also be addressed in the factory layout rather than jig design. By controlling the ambient temperature more closely and doing so in such a way as to heat the jig structure evenly, we should be able to greatly reduce or eliminate this factor. Rather than radiant heaters mounted to the walls, the new factory is to be equipped with forced-air heating systems, which will be a substantial improvement.

The third point, however, is both the most severe and also the most dependant on jig design. This is an opportunity for significant improvement, and is the driving problem explored in this paper. Figure 2, below, plots six sets of data collected across two weeks and illustrates this point. Inboard and outboard tower footprints are outlined in yellow, while piling locations are shown in red.

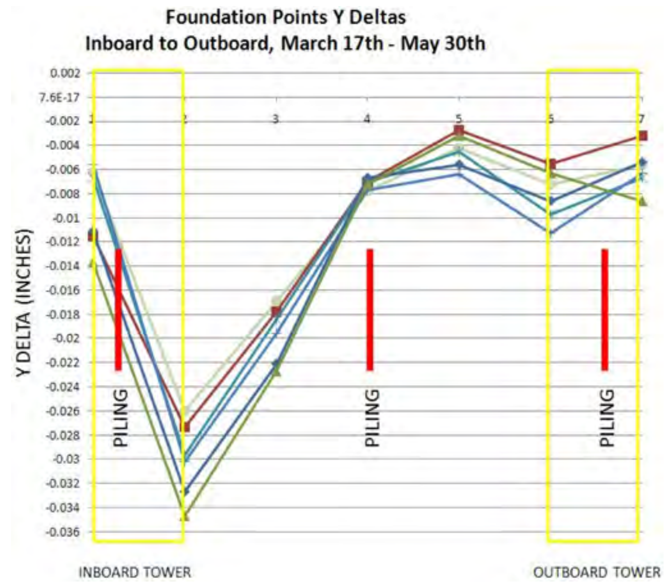

Figure 2. Foundation Settling, Inboard to Outboard

The large sag at the outboard corner of the inboard tower is obvious. Examination of the overall jig design on this project shows that this is the area of the highest foundation loading. The inboard tower is taller and heavier than the outboard tower, and moment loads from the upper beam are resolved here as well. This drives the pressure concentration to the outboard edge of the footprint, essentially tipping the tower about its pilings. Additionally, we observed a dependency between the foundation displacement and the moment loads. That is to say, due to the height of the tower and the geometry of the upper beam, as the foundation settles under the tower the upper beam moves outboard, which in turn actually causes an even more severe moment, feeding the problem.

The way-forward comes in several pieces. First of all, the foundation design was substantially improved, incorporating a thicker pad, more reinforcement, and more pilings. This will not only mitigate the settling issues we saw on the demonstrator wing box jig, but should also serve to greatly reduce the tipping effect caused by sparse pilings. Also, the heating system in the new factory will create a much more hospitable environment for large, precision jig structures.

The final point, though, is the key lesson we are focusing on for this discussion. We will be looking extensively at what can be done with the jig design to reduce the foundation-resolved moment loads. The theoretical benefits of this are two-fold. First, eliminating pressure concentrations like those found on the demonstrator wing box jig should directly reduce the amount of movement seen in the foundation.

Second, given some small amount of settling due to situations beyond our control, a jig with more evenly distributed reaction forces should be more insulated from the motion.

METHODOLOGY

Four major structures are considered to determine the best design approach. Each is modeled in Catia V5 and analyzed in ANSYS, normalizing the results as outlined below. All analysis is comparative. One design approach will be selected for further development, based upon the following criteria:

1. Jig Height: The jig height should be minimized to improve crane handling clearance. At the time of design, the ceiling height of the structure has been fixed, leaving a limited amount of vertical space for the factory crane and associated handling equipment. If the jig's height increases, this could easily drive the cost and complexity of handling equipment substantially higher.

2. Jig Weight: The jig weight is a major contributing factor to foundation loading. It is also a very good indicator of overall structure cost. All other things being equal, a lighter structure will almost always be more cost effective to source, fabricate, ship, and install.

3. Live Load Deflection: This is the maximum calculated deflection of the structure when subjected to a representative aircraft part weight distributed along the upper beam. The wing for the C-Series will be manufactured with the leading-edge facing down, so for this analysis we will be using the weight of the rear-spar subassembly. To ensure a relevant comparison between structures, this deflection will be normalized to 0.002″ for this analysis.

4. Machine Load Deflection: This is the maximum calculated deflection of the structure when subjected to a drill force load of worst-case magnitude and position. In this case, the largest drill forces will be seen in the pylon area as well as the landing gear brackets at the inboard trailing edge assembly, of which the gear area is clearly the more severe location. To ensure a relevant comparison between structures, this deflection will be normalized to 0.020″ for this analysis.

5. Thermal Deflection: Because of the widely varying boundary conditions of the structures to be analyzed, we can expect very different internal stresses to accumulate when subjected to temperature changes. Thermal changes are a constant challenge for large precision tooling such as this, so we must ensure that each structure considered behaves predictably and acceptably under real-world conditions. To simulate an ambient temperature change, the floor is held at twenty-two degrees Centigrade while the top of the beam is raised to twenty-eight degrees Centigrade. The steady-state temperature gradient achieved simulates a six-degree temperature change within the factory.

6. Floor Pressure: This is the maximum calculated floor pressure induced into the foundation due to a combination of the live load, machine load, tooling weight, and jig self-weight. It is theorized that a lower peak floor pressure could not only reduce the risk of significant foundation movement, but also help to isolate the tooling from the impacts of any settling, creeping, or shifting of the foundation on which the jig is built.

Each of these metrics are critical to the overall success of the structure and, though floor loading is the primary focus of this paper, the other factors must still meet acceptable limits if any foundation pressure benefit can be realized.

ANALYSIS

CASE #1: BASE-LINE

The base-line design approach is a picture-frame structure with thermal expansion rail located at the base of the outboard tower. To add rigidity, the chain of leading-edge modules is loaded in tension, but it lacks the section to support any moment. This is illustrated schematically in figure 3.

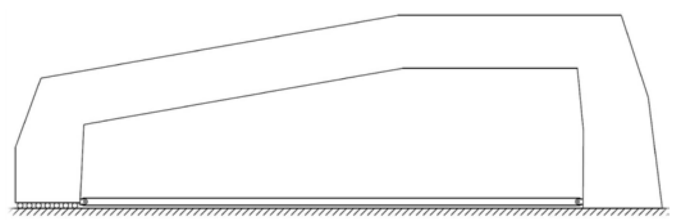

Figure 3. Case #1: Base-Line Schematic

The strength of this design is expected to be a very high relative rigidity due to the full moment support at all four corners and the added strength afforded by constraining both ends of the leading-edge module chain.

However, there are concerns that this design could have undesirable thermal behavior and high floor loading. Because the thermal expansion joint is placed under the outboard tower, a temperature gradient will generate potentially significant internal stresses. Also, because the leading-edge modules are loaded in tension only, some additional moment load must be resolved at the floor.

CASE #2: OPEN FRAME

The first alternative to the base-line case is very similar, but with one key difference conceived in an effort mitigate the concerns outlined above. In this “Open Frame” design, the thermal expansion rails have been moved to the top of the outboard tower. This means that the leading-edge module cannot carry any tension load and we lose any structural benefit that may have given us. This is illustrated schematically in figure 4.

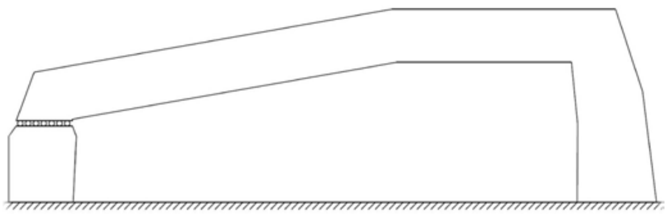

Figure 4. Case #2: Open Frame Schematic

This design is expected to be somewhat less rigid than the base line. However, because the thermal expansion joint interrupts the picture frame, there can be no large internal thermal stresses. Deflection due to a temperature gradient is expected to be very predictable.

As with the base-line case, all four corners of this frame are capable of supporting moment loads, which means that they will be resolved at the floor. This could cause high floor pressure.

CASE #3: SIMPLY-SUPPORTED BEAM

The third case to be considered is a textbook simply-supported beam, incorporating pivots at each end of the upper beam. This approach is intended to reduce the moment loads transmitted to the foundation, hopefully reducing peak pressure. A thermal expansion joint is located at the top of the outboard tower, and the leading-edge modules do not contribute structurally. This is illustrated schematically in figure 5.

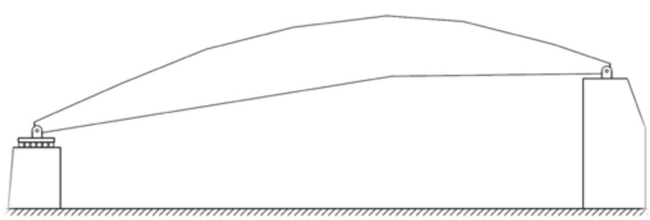

Figure 5. Case #3: Simply-Supported Beam Schematic

This approach should effectively eliminate the moment reactions at the floor, reducing the floor loading to compression only. Also, as with case two, the thermal expansion joint interrupts the picture frame, so thermal deflection should be mitigated.

However, by removing the ability of the top of each tower to support moment loads, we have substantially compromised the overall rigidity of the structure. Normalizing this design approach for rigidity could drive jig weight up, which will in turn increase floor loading due to self-weight.

CASE #4: LOW PIVOTS

The final design approach to be considered is an effort to capitalize on the perceived benefits of cases one and three. This design incorporates leading-edge module tension for rigidity and pivots to isolate the foundation from moments. A thermal expansion joint is located under the outboard tower, and each tower is free to pivot about its base. The joints on top of each tower are fully moment supporting. This is illustrated schematically in figure 6.

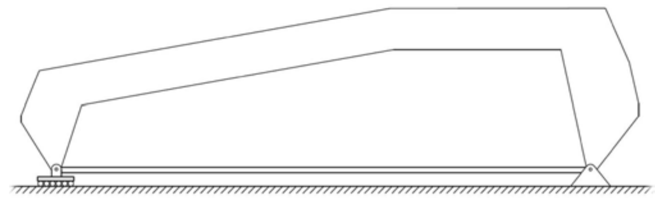

Figure 6. Case #4: Low Pivots Schematic

Though this is the most outlandish of the proposed cases, it shows a great deal of promise. The large section of the beam coupled with the support afforded by the leading-edge module chain should result in a relatively high rigidity, while the pivots will prevent any significant moment from being transmitted to the foundation.

There are two major concerns with this approach. First of all, the thermal expansion joint does not interrupt the picture frame, meaning thermal deflection could be significant. Also, because the pivots must be very close to the ground, it will be difficult to evenly distribute the compressive load to a large footprint; even though the moment load can be eliminated by the pivots, the peak pressure may still be high.

RESULTS

Each of the outlined cases were modeled in Catia, normalized for live-load deflection and clamp deflection, and analyzed in ANSYS. The results for each of the critical metrics to be considered are summarized on table 1.

Table 1. Analysis Results

Results	Case #1: Base-Line	Case #2: Open Frame	Case #3: Simply-Supported	Case #4: Low Pivot
Jig Height (in)	276	284	293	273
Jig Weight (kip)	67.8	74.5	93.8	70.7
Live-Load Def. (in)	0.00200	0.00198	0.00199	0.00193
Clamp Def. (in)	0.0195	0.0184	0.0210	0.0189
Thermal Def. (in)	0.0208	0.0055	0.0075	0.0288
Floor Pressure (psi)	187.6	232.5	233.4	254.3

Note first the peak floor pressure numbers. Cases three and four both added pivots to the design for the express purpose of reducing the moment transferred to the floor, thereby limiting the peak floor pressure. We can clearly see that this was not realized. Both cases add complexity for little or no benefit.

Also note that case three is significantly larger and heavier than the others in order to achieve similar deflections under load. The amount of rigidity lost by eliminating the towers' ability to support moment loads took a great deal of extra steel and section to compensate for.

The thermal deflection seen in cases one and four (both cases with tension-bearing leading edge modules) is unacceptable. This is something that is inherent to the design concept and there is little to be done to mitigate it. These cases must be discarded.

With cases one and four eliminated, we see that case two is the clear winner, superior to case three in all metrics measured, most notably thermal deflection and weight.

SUMMARY/CONCLUSIONS

Of the four design approached considered, the simply-supported beam and low-pivot designs fail to deliver on reduced floor loading, the simply-supported beam design is grossly overweight, and the base-line and low-pivot designs suffer from unacceptable levels of thermal deflection when subjected to a six-degree gradient.

The open frame design is the clear winner of this comparison and has been chosen for further development. While it is heaver and larger than the base-line and low-pivot designs, the thermal benefit is undisputable.

GOING FORWARD

Based on the above conclusions, the open frame design was carried forward through further optimization, detailed design, and manufacture. Four structures have now been erected on-site at the C-Series factory in Belfast and have, to date, validated the calculations and expectations of the author (figure 7).

Figure 7. Open-Frame Design Realized

Evaluation of the foundation stability is ongoing, but initial reports are positive. Though this exercise validated the conventional wisdom and the way-forward has not been a revolutionary one, we are confident that, for this application at least, the foundation loading has been minimized to the full extent feasible.

CONTACT INFORMATION

Michael Carr is a mechanical engineer with Electroimpact, Inc. in Mukilteo, WA. For more information about this and other custom tooling and machines for aerospace automation, contact the author at michaelc@electroimpact.com. The Electroimpact website is http://www.electroimpact.com/.

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