

Reciprocal Frame Roof of the Events Beacon for a Tech Office Building in California

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1. Introduction

This reciprocal frame roof is part of a larger project consisting of two adjacent buildings located on the campus of a global technology giant in Sunnyvale California.

The first building is a six storey, 29,000 m² mass timber office structure which includes a large single storey cafeteria to the north, and an 1,800 m² double height, single storey event space called the Events Beacon to the south. The Events Beacon is designed to host the company's TED style presentation events. The roof of the Events Beacon consists of a reciprocal frame which is the subject of this presentation.

The second building is a 3,000 m² mass timber fitness centre, which consists of a double height space along the front façade and a mezzanine along the back.

2. Project Context

The Events Beacon is a 7m tall, single-storey rectangular volume abutting the office building to the north. It houses a large open presentation space to the east and the main entrance to the building to the west. The space is surrounded by 1.8 to 2.8m long load bearing CLT blade wall elements which are oriented at 45 degrees to the building edge on a 2.1m spacing. The wall elements are connected by glazing, creating a dynamic sawtooth shaped façade, with controlled sun ingress into the presentation space while offering a connection to the outside. The reciprocal frame roof extends continuously over the event space and main entrance to the building.

One of the main programming requirements for the Events Beacon was to maximize flexibility by minimizing the number of interior columns. The architect also expressed an interest in a 45-degree two-way grid structure, also with a 2.1m element spacing, which would relate to the perimeter blade walls.

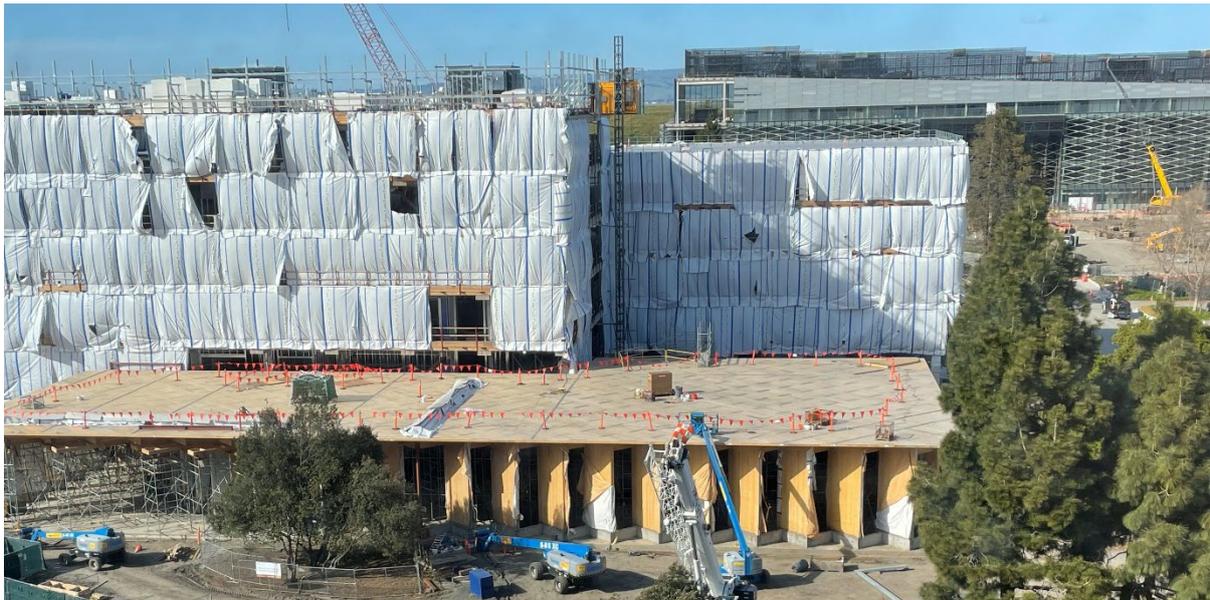


Figure 1: Overall view of the office building with the Events Beacon in the foreground; Credit: Equilibrium.

While a simpler one-way beam structure running at 45 degrees with non-structural bridging elements would have achieved a similar effect, we proposed a reciprocal frame solution to achieve a shallower, more «honest» and true two-way system. Another key advantage

of the reciprocal frame solution is that all connections are in shear, avoiding the introduction of hundreds of moment connections which would have added significant cost and complexity. The reciprocal frame, made entirely of 4.2m elements, also avoided the need and additional cost of trucking 39m long glulam beam elements from British Columbia to California.

3. The reciprocal frame

The 1,800 m² flat reciprocal frame consists of over 250 elements, most of which are 4.2 m long, oriented at 45 degrees on a 2.1 m grid spacing. The grid elements align with the ends of the perimeter load-bearing blade walls. The decking consists of 5 ply, 139 mm thick CLT (Cross Laminated Timber) panels spanning between the grid elements and provides the lateral load resisting diaphragm. The entire grid is overbuilt with 15 cm deep blocking which is cut out as needed to allow services through.



Figure 2a: Exterior view of the reciprocal frame during construction; Credit: XL Construction.

The supports for the grid consist of the perimeter CLT blade walls, two shallow cambered upstand steel box beams which hang the grid from above, and two steel columns concealed in the storage room partition walls at the east end of the space.

To optimize the two-way grid structure, the rectangular roof plan was roughly divided into two square areas with the introduction of a cambered upstand steel beam above the roof plane. At the south-west edge of the grid, the blade columns create a funnel shaped no-vention and opening leading to the main entrance to the building, leaving the south edge of the frame unsupported over a 21 m span. A second cambered upstand steel beam was then introduced to support that free edge of the grid. Also, two steel tube columns were introduced within the partitions of the storage room in the eastern half of the space which is larger and has significantly longer spans than the west half of the roof.



Figure 2b: Interior view of the reciprocal frame during construction; Credit: Equilibrium.

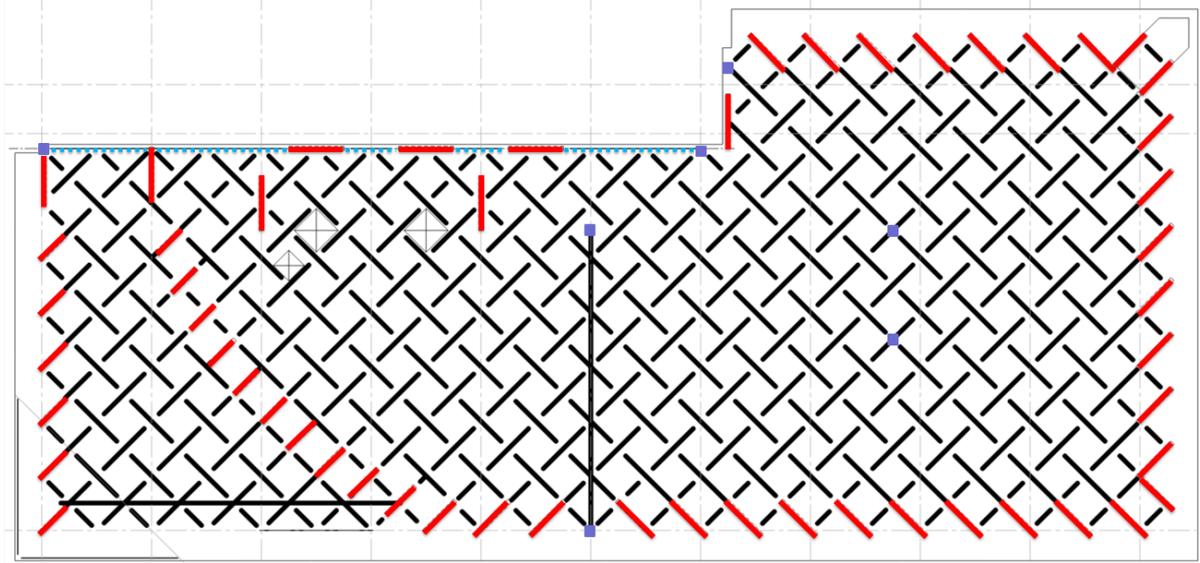


Figure 3: Plan view of the reciprocal frame showing the supports; Credit: Equilibrium.

4. Connections

Reciprocal frames consist of short elements which depend on each other for supports and the frame is unstable until it is completed. Hence the name «reciprocal». For this reason, one downside to reciprocal frames is that they must be shored. Also, because the two-way reciprocal frame is continuous over the irregularly distributed supports, connection loads vary significantly and often reverse as the grid approaches support points.

The initial concept for the connections consisted of custom «Z» shaped hangers, designed for different load ranges and which could be installed on the beam ends in the shop and easily reversed where required. This approach would have allowed for a relatively simple installation procedure.

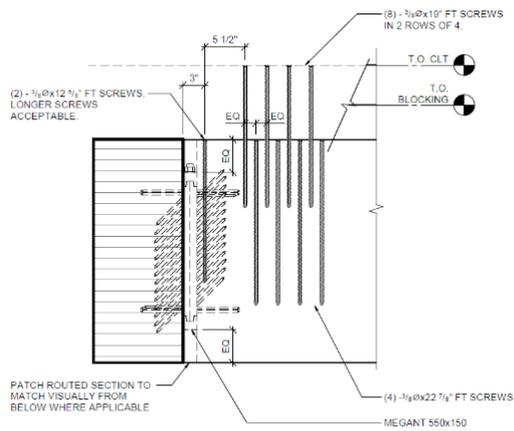
**R1 HANGER**

Figure 4: Typical reciprocal frame connection detail; Credit Equilibrium

At some point during the design however, the effects of shrinkage at the connections were assessed. While shrinkage effects in «Z» type hangers are not an issue in most structures, the effects are significant here due to the reciprocal accumulation of shrinkage through hundreds of mutually dependant connections. Our estimate of the overall impact on the deflection of the grid was estimated to be in the order of 10cm, which was excessive.

We therefore switched to a connection system that joined the beams to each other at the centreline, eliminating shrinkage effects from beam to beam. Ricon connectors would have been the most economical but could not be installed in a closed loop and installed from the top. We therefore settled on Megant connections, as they can be installed from the side and allowed us to close loops within the reciprocal frame.

5. The Upright Beams

The depth of the two strategically located upright beams was limited as they are visible above the low Beacon roof from the adjacent office building. With spans of up to 21 m and a maximum depth of 40 cm, the beams are cambered 6 and 8 cm respectively to reduce the predicted overall deflection of the reciprocal frame. This allowed us in turn to reduce the maximum deflection of the roof from about 10cm to 4cm.



Figure 5: Upright beam hanger detail with load cells; Credit: Equilibrium.



Figure 6: Load cell data acquisition; Credit: Equilibrium.

The upstand beams were effectively designed as springs to be preloaded through a carefully planned sequence as the grid lay flat on the shoring towers, to achieve a zero deflection condition along the beamlines, mimicking a rigid support at those locations.

An extensive and complex sequential analysis of the upstand beam preloading and grid de-shoring procedure was carried out to ensure that the grid elements and connections would not be overstressed. The threaded rods hanging the grid from the upstand beams, as well as several strategically selected shoring tower legs were instrumented with load cells which were connected to a laptop located on the roof. This allowed us to carefully monitor load levels in real time at each stage of the procedure and compare in-situ load readings with the predicted values obtained from the preloading and de-shoring analysis.

Data processing software, which we developed specifically for this purpose, allowed us to update our preloading and de-shoring models on the fly and update our analysis and make adjustment in real time.

This grid is to our knowledge one of the largest flat reciprocal frame structures in the world. As a prominent feature in a space designed to promote the exchange of ideas, it embodies our client's promotion of innovation and their emerging commitment to more sustainable construction.