SOFTWARE SOLUTION

SOLVING THE STEEL TO CONCRETE CONNECTION CHALLENGE

A WHITE PAPER PRESENTED BY

HILTI New Civil Engineer

KEY STATS

33%
Percentage of engineers who say optimising connection design is challenging

10%
Engineers who say it takes more than eight hours to design connections

INTRODUCTION

Designing steel to concrete connections is a key, safety-critical task on many construction projects. Correctly done, these connections can ensure a structure remains serviceable for many decades. Incorrectly done and disaster can ensue, with the potential for serious incident and even loss of life.

Yet despite this criticality, engineers who regularly design steel to concrete connections often struggle because there is no software to design the different elements of a steel to concrete connection as a whole.

All too often multiple methods are needed to design the different elements in a single connection which increases the time taken for the connection's design. The whole process is difficult and time consuming and, with little time for iterations, designs put forward are frequently not as efficient as they could be.

Currently, it is a common practice to use a number of different tools to complete the design of steel to concrete connections, including hand calculations, with each addressing a different element of the connection – anchor, baseplate, weld, stiffener – with the engineer following several technical guidelines.

This White Paper looks at the creation of PROFIS Engineering software from Hilti, which has been developed to address these very issues. It considers the challenges, explores the research that led to the solution, and demonstrates exactly how the software ensures all four key connection components can be designed in compliance with European Technical Standards in a fraction of the time it currently takes to undertake the task.

EXECUTIVE SUMMARY

When Hilti noticed a trend at the start of this decade in customers reporting difficulties designing sophisticated steel-to-concrete connections, the global construction technology giant set about finding a solution.

The first step was understanding the problem. Discussions with users of Hilti's existing PROFIS Anchor software revealed a desire from engineers to look beyond the details of an anchor to work on the full interface between the two structural materials.

This meant looking at how welds, stiffeners and – critically – base plates behaved in connections on real buildings to allow designers to maximise the efficiency of proposals for their own future schemes.

Hilti – which has more than 29,000 employees working across 120 countries – then proceeded to formulate a series of questions for a more scientific survey to dig deeper into the scale of the issue across the industry.

More than a third of respondents to this survey of civil engineers said creation of a programme that would model anchors, base plates, welds and stiffeners would be valuable to them.

An exploration of the mathematical theory behind connection design was carried out by Hilti's in-house research and development department, with the work co-ordinated by global product line manager Mario Fitz, technical marketing manager Jörg Appl and senior trade manager for engineering Oliver Geibig.

They analysed a raft of experiment data from a number of sources to work out the point at which increasing the forces on an anchor affected the failure point of the overall connection.

Their big discovery was that while standard engineering design relied on treating a base plate as rigid, the best way to understand the precise nature of stresses on the different elements of a steel-to-concrete connection was to assume a flexible base plate and closely control the overall interface through a raft of variables.

Going into the forensic detail needed to safely and optimally draw up a flexible-plate design, looking at welds, stiffeners and anchors as well as the different forces on a structure and other variables, was simply not viable using existing methods.

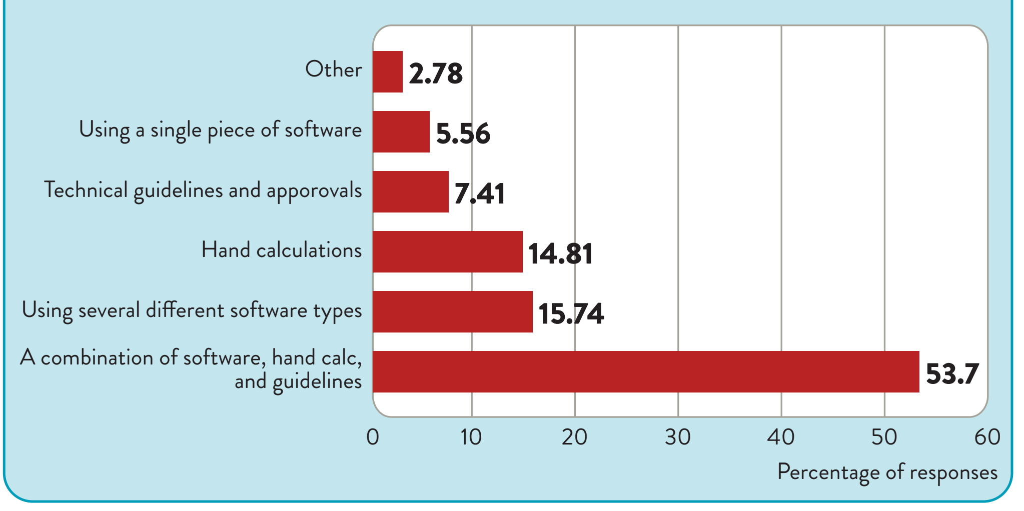
A new piece of software was required to allow proposals to be honed by high-level trial and error, reworked at the click of a button until fine-tuned to maximise efficiency. If this could be achieved, the time and material tonnes required to create a single connection between steel and concrete could be slashed.

A period of advanced coding and programming was undertaken and after testing and commissioning, PROFIS Engineering was launched on 1 February this year, the final step in Hilti's journey to solve this particular problem for customers – and the first opportunity for civil engineers to get to grips with more efficient connection design.

CHALLENGE

To understand the scale of the problem Hilti first undertook a global research project, reporting in April 2017. Its findings gelled closely with findings from a supplementary survey

HOW DO YOU DESIGN THE DIFFERENT ELEMENTS OF THE STEEL TO CONCRETE CONNECTION (anchor, baseplate, weld, stiffener)?



carried out in conjunction with *New Civil Engineer*, which asked 100 practising civil engineers to consider their experiences of designing steel-to-concrete connections.

More than half of the respondents to *New Civil Engineer*'s survey admitted to using a mind-boggling combination of various pieces of software, hand calculations and technical guidelines and approvals to design anchors, baseplates, welds and stiffeners to tie together the two materials. Just 6% said they used a single programme for the whole connection.

One in 10 engineers polled said that designing a steel-to-concrete connection, and producing a report for surveyors that justified it, typically took more than eight hours. More than half of those surveyed said it took at least two hours.

> **"To get the most precise design you need to look at the stresses on all elements of the connection**

Respondents highlighted concerns about oversight of concrete-to-steel interface design. "It can often be a topic that falls into the gaps between the designer of the steelwork elements and the concrete elements," said one.

Optimisation of an overall connection was cited as an issue by almost a third of those completing the survey. A similar proportion saw a lack of a single piece of software to do this job in the whole as a problem.

Hilti's research, supplemented by *New Civil Engineer*'s survey, framed the challenge: the company needed to find a way to enable skilled engineers to put their skills to use to improve the efficiency of final steel-to-concrete connections and of the process of designing them.

Hilti soon realised that the assumptions conventionally made for such designs were hindering the arrival at the optimal solution.

"Most concrete-to-steel designs assume a rigid plate, but in reality there is deformation, and to get the most precise design you need to look at the stresses on all elements of the connection – the anchors, stiffeners, base plate and welds," says Hilti product manager for technical software across northern Europe Carlos Taborda. "This introduces a complexity that requires detailed analysis."

Tarborda: Software halves design times

Taborda says conforming with Eurocodes makes it "almost impossible" to use this flexible-plate method of calculations to come up with the best connection design. He adds that abandoning guidelines altogether and going for all-out flexibility relies on engineering judgement but that this can potentially be dangerous.

METHOD

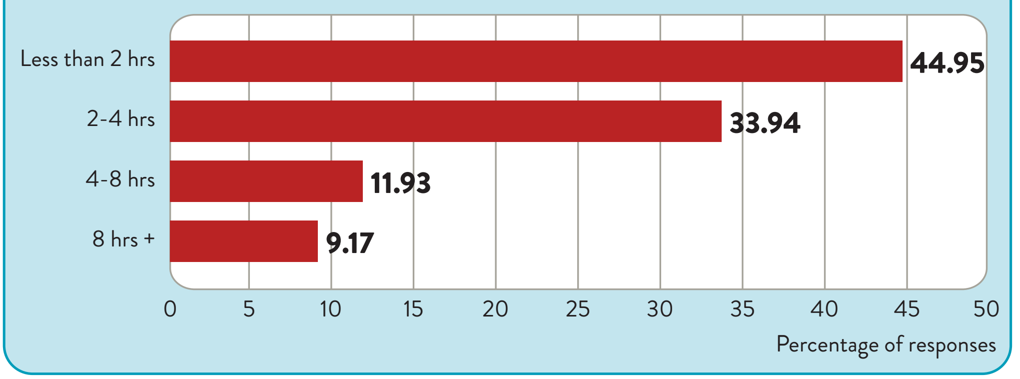
Hilti's rigorous testing process came up with a sweet spot. The firm found that if the increase in anchor forces on a flexible plate compared to those that would be expected using a rigid equivalent is less than 10%, there is no impact on the total failure loads of the connection.

This was explained in detail in a 2018 paper by Fitz, Appl and Geibig, entitled *Comprehensive base plate and anchor design based on realistic behavior – new design software based on realistic assumptions.*

First, the paper helpfully set the context of the engineering problem.

"The design of base plates and their fixtures anchored in concrete is important for planners and users," explains the document. "Modern fixtures allow concrete structures to carry heavy loads, and these safety-relevant joints must be designed with precision. Furthermore, the planning engineer is liable to the building owner for economic construction…

ON AVERAGE HOW LONG DOES IT TAKE TO DESIGN A TYPICAL STEEL TO CONCRETE CONNECTION AND PRODUCE A REPORT?



> **We can save up to 50% in time by doing the checks with one piece of software**

to design the structure according to methods that allow the best possible use of the fixtures."

The paper goes on to explain that under the relevant regulations, a rigid base plate must be assumed if the load of connection fixtures has been determined by the commonly used elasticity theory.

However, the document adds that no clear rules are in place as to when a base plate should be deemed sufficiently rigid.

"The assumption that the base plate does not deform under applied loading actions determined on the basis of the elasticity theory is not always guaranteed for base plate thicknesses in standard practice," adds the paper.

"One of the assumptions for a rigid base plate is that the resulting concrete compressive force acts on the outer end of the base plate. If, however, in contrast to the assumption, a flexible base plate is used, this leads to a reduction in the lever arm of the internal forces and thus to higher loads on the fixture. In extreme cases, a plastic hinge is likely to form in the base plate at the edge of the profile, whereby the resulting concrete compressive force will move towards the edge of the profile."

Hilti's experts demonstrated that if substantial deformation occurred as a result of such a plastic hinge forming in the base plate on the tension side of the connection, the plate corners could become compressed against the concrete, inducing additional prying forces which, in turn, could lead to an increase in the tensile force in the anchors.

"These prying forces can also occur with larger base plate protrusions, flexible base plates and predominantly tensile loads," said the paper. "The load-distributing effect of the base plate is prevented by the considerable deformation of the loaded base plate, which can lead to significant overloading and premature failure of an anchor within a group."

To accurately assess the rigidity of a base plate and its fixtures, as well as the welds and attachment, the authors found it was necessary to better understand the true nature of load-deformation of the individual components and thus take equilibrium and compatibility conditions into account.

The role of Eurocodes in the Hilti research was set out in the paper.

"The base plate, the welded-on profile and the stiffeners around the welds are described taking into account the material properties according to EN 1993-1-1 or EN 1993-1-5, modelled according to the finite element method and provided with an elastic-plastic (welds) or elastic-plastic, linear hardening material law (profile, stiffeners and base plate)," it said.

"The concrete response is formulated on the basis of the concrete properties according to EN 1992-1-1, whereby the spring stiffness of the concrete is based on the Winkler-Pasternak model."

A separate research project was conducted by Hilti to determine load-deformation behaviour of anchors. Taking into account pre-stress, anchor material and coefficient of friction, the study showed that the anchor rigidities obtained in some cases deviated significantly from the values in the corresponding approval documents.

"This can be explained by the fact that the displacement values of the anchor published in the corresponding documents/evaluations were determined under a different philosophy – maximum displacement values – than is required for determining the rigidity of the fixture for the design of the base plate – minimum displacement values," explain Fitz, Appl and Geibig.

To check base plate rigidity, anchor loads calculated according to elasticity theory are compared with anchor loads that take account of equilibrium and compatibility conditions on the basis of realistic assumptions of the load-displacement behaviour and the stress-strain curves of the individual components and assuming a rigid base plate. By comparing the anchor loads of both methods, the gap between theory and practice can be determined.

Experiments were undertaken to determine mean failure loads of anchor groups as they related to the calculated failure load taking into

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account the elasticity theory as a function of highest loaded anchor of the group.

These tests took into account anchor groups with four and nine anchors under uniaxial and biaxial bending in non-cracked concrete. In the tests, cast-in headed studs and post-installed anchors were used. The plate thicknesses used were those calculated using the stress.

This work was undertaken to estimate to what extent a deviation of the most heavily loaded anchor of a group from the calculation according to the elasticity theory affected the overall group's load capacity.

On the basis of the available test values, it was shown that with a deviation of the anchor loads of the most loaded anchor of a group of approximately 10% – between rigid and realistic baseplate assumptions – the mean failure load of the group fixture corresponded to the mean group failure load calculated according to the elasticity theory.

This meant that in the case of approximately 10% deviation in the anchor loads between the rigid plate and the flexible plate, no negative influence on the load bearing capacity could be observed in the tests.

After a period of coding and software development by Hilti's in-house team, PROFIS Engineering was created to carry out the huge number of detailed calculations required to take engineers to the best connection designs for their projects.

SOLUTION

The essence of PROFIS Engineering, which supercedes the current PROFIS Anchor software, is that it uses bespoke algorithms to analyse the distribution and impact of stress on all elements involved in structural connections, enabling engineers to use all their skills to maximise the efficiency of joining two key structural materials.

The new approach is based on a robust finite-element solver with accurate material models as well as a unique description of the anchor behaviour to allow a realistic design of the full connection.

Hilti worked with Czech-based structural engineering software developer Idea StatiCa's to develop the finite element methodology.

It's chief executive Lubomir Šabatka is pleased with the collaboration: "We believe that the new component-based finite element method is the right approach to break the limits of anchoring/footing topologies while keeping safety first.

"We put the CBFEM into the core of our product, Idea StatiCa Connection, and Hilti has integrated it in its new PROFIS Engineering Suite." The state-of-the-art software offers tailored solutions for structural engineers, detailers, purchasers and jobsite managers. It facilitates the flow of information throughout the construction team, reducing the opportunity for errors.

Hilti PROFIS Engineering helps engineers improve accuracy and save time through automatic load transfer from structural analysis software.

Applications include designing anchor fastenings for use in concrete and masonry; designing handrails for installation on concrete; and generating CAD and building information models of connections.

PROFIS Engineering can be used to identify anchor item numbers, calculate mortar volumes and prepare bills of materials as well as check anchor item numbers, base plate and anchor arrangements on a site.

Compatible with Android and Apple products, supported by Windows 7, 8 and 10, PROFIS Engineering comes in a variety of licences to suit individual and company needs.

It is an intuitive piece of software that allows skilled engineers to input the facts and figures pertinent to their project, select various options using their own judgement, and very quickly see what the impact of their choices is on the design.

Within seconds, the software uses bespoke algorithms to look at everything and analyse stress distribution and deformation.

It gives a split-screen view of how a rigid plate would behave and how a flexible one would differ. If you confirm you are happy with the base plate deformation then the software tells you the extent of deviation from rigidity. If it is above the 10% limit

KEY STATS

50%
Reduction in design time promised using PROFIS Engineering

10%
Percentage who say it takes more than eight hours to design connections

then you can go back and reassess using a mixture of suggestions from the programme and your own expertise.

It is a process not dissimilar to changing the dates and times of your flights, and the must-haves for your hotel, to see how the cost of a holiday changes.

"Without the software it would take so much longer, and you would have to start from scratch when you realised how far over the deviation limit you were," says Taborda. "Now you can very quickly change the size, position of anchors, put in more welds, stiffeners, use a thicker plate and so on."

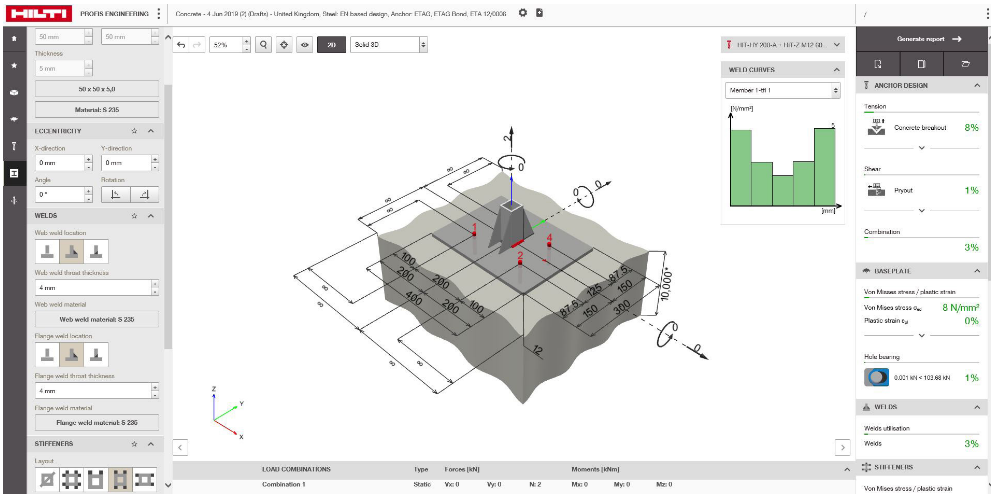
PROFIS Engineering software immediately tells the user if their designs would lead to more than 10% deviation in loads. The package then allows an experienced engineer to go back and adjust elements of their proposals, with certain prompts and suggestions, to get to below 10% with the safest, most efficient set of values.

Hilti says connection design time can be reduced from an hour to 30 minutes and indications from the market are that this might be conservative.

WML Consulting Greg Matejko certainly thinks so. "A design that used to take one hour can be done in 15 to 20 minutes using PROFIS Engineering," he asserts.

"Before we had access to PROFIS Anchor, assessing fixing loads had to be manually and would then be counter checked with the Hilti technical team. Assessing the stiffness of the baseplate to make sure it was performing as a rigid element was still a challenge even using PROFIS Anchor. We used to produce a check of the stiffness of the baseplate, and a separate calculation for the associated fixings as two separate systems and it was not easy to assess the interaction between both.

"The feature in PROFIS Engineering that compares rigid and flexible baseplate designs simplifies the design process. We used to design for an ideal rigid baseplate but now, with PROFIS Engineering, we are able to assess the same design case as a flexible baseplate. This allows a reduced baseplate thickness, and optimises the utilization of the anchors, with the associated reduction of cost for the customer. The benefit is to be able to have reliable calculations for all elements in the steel to concrete connection (anchor, baseplate, welds, stiffeners, concrete and profile), and the reduction of the time required to do those calculations with an easy to use software with an intuitive interface."



A 3D visualisation of the connection in PROFIS Engineering

Marianne Johannsson, structural engineering manager at Balco Group agrees PROFIS Engineering will save time: "Design of a plate (full connection including anchors, stiffeners, base plate, etcetera) might take up to four hours plus two hours to create the report. PROFIS Engineering could save us up to 50% of the time. We've been waiting for this!"

Per Jørstad, structural engineer at Sweco, agrees: "We can save up to 50% in time spent – from two to six hours to one to two hours – by doing all checks with one piece of software."

DEMONSTRATION AND COMMUNICATION

As well as producing a background paper to accompany the new software, and running training courses, Hilti has been able to communicate the benefits to customers in a number of ways.

Appl spoke about PROFIS Engineering in a recent Hilti-run webinar: "The rigid base plate assumption is not a Hilti invention, it is a basic philosophy of Eurocode 2," he said. "If I want to design anchors according to Eurocode 2, I have to provide a rigid base plate."

During the webinar, Fitz used a model to demonstrate that even under tension loads, a non-rigid base plate can lead to higher anchor loads than were anticipated in an initial design assumption.

A rigid base plate would lead to equal load distribution on all anchors under a centrally applied tension force but in reality, with a non-rigid base plate, you have a less stiff system and the middle anchor of three would have a much higher load than others, and this would not be accounted for in the original design.

"A demonstration shows that compression forces lead to extreme high forces below the base plate, which can lead to crushing of concrete," said Appl.

"The non-rigid base plate can influence the anchor forces as well as other parameters. There is a basket of parameters influencing baseplate rigidity: baseplate size, stiffeners, baseplate thickness, anchor size, profiles size, anchor type, anchor position and distance of anchor to edge of baseplate."

Fitz spoke about the questions from customers that had prompted Hilti to start the long journey to launching PROFIS Engineering.

"You asked us what makes a

rigid base plate – is it 12mm, 16mm, 20mm? The answer is easy – it depends! It depends on all the parameters listed above.

"We also heard from you that our software for designing anchors was great but you also needed to design base plates, stiffeners and welds. Now we offer a piece of software to do the full design."

The programme allows you to define a base plate as rigid or flexible, and also looks at profile, stiffeners, welds, anchors and concrete.

"In the software you define the application – all the parameters," said Fitz. "Then you hit calculate. The software will help you understand how far off the theoretical rigid plate assumption you are. If you are far off you are using a lot of engineering judgement. We provide a comprehensive design report that you can present to verification engineers or building authorities."

A key step of the process is the 3D visualisation of the connection.

"In the 3D interface you can define most of the geometrical parameters, the loading and select what kind of welds you want, and whether you want stiffeners. You can run the results. In the background, every component is assessed and within just five to 10 seconds on average, you have results. On the left hand side you see the results for the rigid base plate; on the right you see realistic behaviour."

Getting a firm grip of what the differences here meant in practice was a key stage for Hilti in developing the software.

"There is no guideline to tell you what a rigid base plate means in reality, so we have done a lot of effort in research and development," said Fitz. "Up to 10% deviation from rigid, we saw no difference in failure loading. Far beyond this you must be aware you could be outside anchor design guidelines.

"If the loads of the single anchor is deviating within 10%, this has no effect on the ultimate performance of the group of anchors."

The software runs so many calculations that it can do a range of bonus applications for busy engineers – such as producing design verifications according to Eurocodes for anchors, plates and welds.

"You get a summary of results on the right hand side of the screen," says Fitz. "This also shows stresses, strain and deformation.

"If you don't want to allow any yielding in a weld you can select this parameter and the software will work on that basis. You define the problem, the software gives a solution."

Although the software performs magic that is almost impossible by hand, it is designed not to stray beyond the control and comprehension of man.

"Formulas, code references and intermediary results are always shown in the report. It is not a black box. You can follow the steps and feel good about the process," says Fitz.

"There are lots of tips and tricks that Hilti experts can share with you to help you go through your iterations quickly and get a design that works for you."

Hilti ran thousands of tests to come up with the correct non-linear behaviour of the anchor, and is able to demonstrate its findings in training.

"The software tells you whether your application works or not. You then need to decide which parameters to change."

CONCLUSION

Hilti says the design time taken for one individual connection is slashed by an average of 50%, give or take depending on the complexity of the calculation.

The figure is based on extensive pre-launch real-life testing with several large engineering firms throughout Europe.

Add cloud access which means users can share files and work collaboratively and report print outs that give full and detailed explanations for results, and the implications could be huge.

"Put simply PROFIS Engineering software reduces steel to concrete design timescales by half," says Taborda.

"And there are potential additional savings in material and operative time as well as health and safety benefits if you are drilling fewer holes, the benefits for everyone in the supply chain are clear."

● **For further information on PROFIS Engineering visit: http://hilti.to/qdfsxj**

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