Open Sectioned Crane Runway Girders with Arbitrary Profile Geometry

Chapter 6 – Crane Rail Alignment and Load Specification

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By choice, many of us set higher priority tending to problems that we "think" are more preeminent or more important, or to certain issues we feel more comfortable to deal with, etc. than paying needed attention to (1) salient topics "misidentified" as less significant or (2) those serious matters being "mistaken" as unimportant.

Some of us often rely on *Basic Structural Engineering Instincts* getting by with barely good-enough proficiency to resolve difficult issues, "thinking" it should not lead to any negative side effects.

One of the approaches or practices making *pseudo logical sense* that often plays into our favoritism is;

> To pick and choose for professional and/or personal convenience doing what "seemed" totally fair and reasonable, like engaging exclusively with those **well-understood** primary-ordinary structural behaviors, which mainly were the results linking to **well-recognized** primary-ordinary *loadings and effects*
>
> > Sort of infallibly taking it easy there and enjoying an easier time. And so it goes by and large, it fosters a well-accepted engineering way of life by default
>
> Barring no question asked, so long as our eye sight is focusing at nothing else but those **easily-comprehended** structural behaviors, then a blurry mix of wrong-could-be-right against right-could-be-wrong styled norm can take charge, ended up affecting everything we do
>
> On the downside,
>
> > Some of our more modest behaviors such as avoiding difficult situations or carelessly making false engineering judgment, etc. can cause undesirable consequences. But, should any disarray emerges as a result, if not restored promptly enough and in the event coupled with untimely mischance, could lead to *catastrophic failures*
>
> The worst part is many of us caught up in it but don't know what had struck

One of the most formidable rationales – took hold for far too long already – was rooted from an unconditional "fancy" in that every variation of structural behavior and response to loads, regardless to the unique nature of each, would fall consistently into the sanctuary of **simple bending**, even when the implication is absolutely untrue on special occasions.

Once the firmly established habit of (1) dealing exclusively with **well-understood** structural behaviors and **well-popularized** stress categories and (2) observing design mandates based solely on "**simple bending supposition**" has dominated the academia and mainstream design practice then, it should be of no bigger surprise why qualifying structures against the **well-recognized** *loadings and effects* singularly has become such an important share of our primary engineering objective, or in many cases the only objective.

On the surface, it seemed nothing seriously wrong when pinning an undivided emphasis on **well-recognized** primary-ordinary *loadings-effects* and those **well-comprehended** primary-ordinary structural behaviors, because to certain structures serving certain functions, it usually works out perfectly with no major side effect, but, hopefully it never does

Clearly that, such an overpitched favoritism and unwavering blind trust into **simple bending** or overplayed design tradition could congeal unawareness − if not ignorance − of the existence of certain ostensible secondary effects being falsely categorized as subordinate-counterpart of those primary-ordinary *loadings-effects*

In essence, those secondary effects, unless demonstrated by calculation or blessed by solid **R&D**, should not be pre-recognized as less important or as secondary by nature without solid proof

Whether to agree or disagree with the foregoing notion isn't a compelling issue here; but all in all, talk is cheap. Trouble or no trouble came out of any event, primary or secondary, must have solid numbers as backup. The concern as to what level of detail is needed to make the point across would depend on what type of structural function is anticipated to provide for what type of industry serving under what type of on-site environment, etc.

The reality is; many secondary occurrences, like many *not so well-recognized* (or well-respected) effects can subsist well below our radar screen doing their magic, often quietly and seemingly harmless, especially when no one looks closely.

Nonetheless, for certain type of structure serving certain type of industry experiencing certain chronic distress, it is extremely important to verify should a certain "secondary" incidents be suspicious of any threat or not; otherwise we may never come to recognize the seriousness of their potential destruction imparted on our structures, if it does in particular to structural members having unusual geometric configuration exhibiting extraordinary behaviors when subjected to *loadings and effects* of extraordinary nature then, what should we do?

6.1 Is There Anything Beyond Primary and Ordinary?

We (or you) can make the call later on, or wait until finishing to the end of the **Chapter**.

This is a subject not often explored, much as we would give earnest thought to hereinafter. Anyhow, take a step back and ponder over, what if we were:

- *So acclimated to implementing conventional engineering routines and putting it to practical use throughout of our career span*

  *During those business-as-usual days, never have the need to deal with the overpowering effects involving **shear center,** or else even when the overwhelming consequences from such effects cannot be ignored in the design, had we or would we just act naïve with no serious forethought, or simply look the other way?*

- *So bought-in with a full-hearted confidence in the good old classic structure qualification approach and had applied the same to everything we do*

  *During the process, never have to worry about design against **metal fatigue**, or else just talk the cheap talk of the subject with aim to retain personal pride or show off to others but abstain from doing anything with it, even though it is part of the design qualification requirement?*

On those issues, enough opportunities were given all along to make an honest assessment for now on our own will, but as some of us so pampered from living in the wonderful simple-bending world for too long, we tend to stick around there only to enjoy the carefree environment more so than facing the unavoidable challenge when time comes to take necessary steps.

As a result, it might be "extremely uncommon" to see anyone would voluntarily step out of a lasting comfort zone for a refreshing change,

So what if someone "willfully endorsed" a (fresher) movement of (1) questioning, could there be any phenomenon being equally, if not more, primary than those being primary and ordinary, or (2) probing deeply into whether if there were other *loadings-effects not so well-researched or well-publicized* but could be of significance that should merit greater mainstream recognition?

Would such a movement catch an overwhelming endorsement? That is open to doubt at this point, but it depends,

On with whatever reasoning being tucked behind – technical or personal – even though "suspiciously" there could be mysterious out-of-the-ordinary *loadings-effects* on the loose somewhere worthy of further study and analysis, but chances are, many among us might not be motivated enough to explore beyond the surface for what it (not) worth

The hold-out for certain long-standing issues that didn't merit widespread recognition could be from lack of interest or for lack of needed knowhow to work it all out, or else from (1) being constrained to stick with a budgetary or engineering resource diet, (2) or simply as no one sponsors or pushes through for the veracity, etc., how disappointing

And so with good enough reason, the *do-only-simple-bending* saga would just carry on, on and on that it turns out everything we do seemed to revert back to the same old same-old

Excuses no more,

For **Crane Runway Girder's** sake, hereinafter we would try <u>to be brief</u> in giving this interesting subject matter an in-depth examination – certainly much further than to anything being *ordinary and primary* – just to see if there were any "out of the blue" findings been undervalued, misconstrued or passed over for all these years if not decades.

But before any of that, we should reorganize there may only be a very fine thread cutting between ordinary and extraordinary, or else we wouldn't know the difference, only if we run the numbers.

By "conventional" engineering awareness, again, we tend to place firm trust to <u>ordinary practice routines</u> that seemed to have worked out well every time in same old ways much as most everyone else does, like judging most matters by the "good looks" even when facing some of the not so bad looking engineering creature such as **Crane Runway Girders**

As we carried on with such "casual or unsuspected" mindset into every project assignment with little questioning or opportune reconditioning, then it befell categorically sensible to maintain our thought process just like that, through the same old way and try repeating the same old approach over and over thus never feel need to come out of the notion:

What's the big deal? **Crane Runway Girder** is no different from any other structures, isn't it?

And in expansion from that perspective, once getting so used to handling <u>ordinary</u> structures subjected to <u>ordinary</u> load applications, easily we would nurture a similar disposition and put through the same ways and means into everything and everywhere including the qualification of **Crane Runway Girder** (**CRG**) design as well

Thereby no wonder many of us may succumb to a commonplace penchant into limited understanding or simply misunderstanding the unusual structural behavior triggered from those *not so well-understood* issues, mainly for lacking serious self-motivated research or dialogue on those seemingly “exotic yet not so exotic” subjects that this article series is all about

And so more than often as consequence we pose no further inquiry into critiquing whether if such across-the-board ordinary practice routines were not all that perfect or even gravely inadequate as far as **CRGs** are concerned

Sooner or later in due time (1) as some of those unusual structural incidents being mistaken as secondary in nature all along or (2) as some of those serious design issues being relegated as conventional events suddenly showed up as part of the project work scope or being called out in the Inspection Reports, or notarized at our desktop pleading for undivided engineering attention, then what do we do or what should we do?

> We have several choices, either (1) striving for a better resolution *for the better for good measure* or (2) just closing our eyes as if not seeing a thing for *one more (last) time*, or for worse (3) denying their existence or even for the worst (4) simply getting around avoiding what should have been resolved, and so forth
>
> No matter what, the choice is for each individual to take on distinctive concern; for instance, imagine, what to do when the inconvenient moment arrives to show and tell *the big difference between flexure bending moment and bi-moment*

But for **CRG** or for other application-specific reasons on unusual or unfamiliar *loads and loading effects*, and for unusual structural behaviors demonstrated beyond ordinary and normal, should we not be more curious to explore further into some of these areas on **CRG’s** behalf?

- *On loads applied at skew with principal elastic axes and/or at offset with* ***shear center****:*
  Is that ordinary or extraordinary?

- *On structure in response to moving wheel loads meanwhile inducing torsion:*
  What is ordinary and what is extraordinary?

- *On justification of structural adequacy against all probable failure modes:*
  What should be primary and what should be (secondary) non-primary?

- *On generalized loading definition*:
  What is primary and what is secondary beyond $\mathbf{P_x}$ and $\mathbf{P_y}$?

To any of those inquiries, whether a good answer, wrong answer, an incomplete or even no answer given is not that important at this stage, as those questions were brought out merely to prime up our awareness of the reality that there could be much more of “what we don’t know or don’t do” veiled behind the curtain. Problem is not many would bother to explore.

> Comparatively speaking, before everything was to be laid open on the table later on in this **Chapter**, it should be fairly straightforward to identify what is normal, primary or ordinary, etc. for general-purposed **non-CRG** structures, simply by studying their response to loads based modestly on their behavior whether it conforms to “**Simple Bending**” or not
>
> But if we try focusing exclusively on **CRG** structures then, it needs a few more pages further into this **Chapter** (and the **next Chapter**, too) to make a point that there is something much more attention-grabbing than matters being *ordinary and primary* just so we know

And for being fair, whether predisposed by what were given in the **Chapter Series** thus far or not, it is rather important for Readers to come up with their own suitable answers firsthand and then compare that with what's coming

Herein we go again, everything starts from engineering basics.

From among many structural engineering issues including some of the design catches and/or misunderstood caveats, out of which those applicable to **Crane Runway Girder Structures** could be summarized as follow:

<u>The Perpetual Design Mandate</u>:

Because wheel loads were applied from the top of crane rail, **CRG** needs to be designed <u>not only</u> for wheel loads applied <u>along</u> all as- designated **XYZ** axes in linear sense <u>but also</u> the effects brought on by the linear or rotational vectors pivoting <u>about</u> principal **X'Y'Z'** axes and the **shear center** whichever as applicable

And thus the girder needs to take on the invariable yet inevitable "side effects" induced *dynamically* from loading eccentricities against the **Shear Center** − collectively categorized as **P-δ** effects as we knew – and that is where the little bit of trouble begins

To avoid troubles whatsoever, the very first thing is do it right; stop pretending that **Shear Center** is located at the rail base

This **Chapter** is mainly about "Load Specification" with **P**, **δ** and **P-δ** being the main ingredient; but, besides the provision of placeholders for their face values – zero or non-zero – what was also disseminated herein is a touch on some of the before-and-after events quietly collecting their tolls behind the scene that the **CRG** must pay up in order to survive, and yet most engineers may not be aware of what's going on

Or so we could articulate what happens,

There are "effects" or "side effects" that would start out as preliminary response from applying the original **P** and/or **P-δ** leading to an "initial round of side effects" – as step one

From which the structure perceives as would be the case of a "fresh increment of load effects" being added on in addition to the "earlier effects" that in combination settles into the "next round of effects" – as step two – in given order to subsequent rounds of effect and then on and on it goes and so forth until it stops

All of that should bequeath a good reason why has the hyphenated compound word *loadings-effects* kept showing up from the very beginning – still kind of confusing for now to some but we'll see to that very soon – and so we think of the complementary phrase to the word "effects" is in reality the "side effects"

<u>The Ongoing Concern</u>:

Not all but "**some**" of the offshoot structural responses from those "side effects" were mistaken either as if not so much to worry or as not exist at all in times gone by – so unqualifiedly negligible compared to the primary events − or as second-classed or unimportant aftermaths, etc. that had gone on for a long enough time

At this juncture,

Since as of this writing the ongoing concern as set out earlier (1) was neither advocated for further study nor condemned as non-issue by the mainstream and (2) there seemed not yet an officially documented "calculation or study" proving that the concern over the "side effects" was whether insignificant or the opposite was true, and so, so what then? Are we worring too much?

Even at present time as the concern being brought to light as some kind of tangential side topic, then by overwhelming evasiveness, it seemed acceptable to forsake the technical high road approach by reducing these "non-trivial effects" into "secondary side effects," which is confounded as not so ominous or of no importance, or not even exist, etc.;

Perhaps truth is inconvenient after all

The Consequence:

Ignoring or mistreating what is not so negligible in realism on **CRG's** behalf would certainly fail the self test on "*The loading effect augmented beyond the definition of simple crane wheel arrangement and loading magnitudes, etc.*" drawn after one of the exemplified concerns addressed at the beginning of **Chapter 5**

One might have better measure of the scope of problem we are facing in the industry if only seeing it eye to eye with the coverage on **Unsymmetrical Sectioned CRG** up to this **Chapter**.

Scattered along the way were assertions uttered in various information packets that, already, a certain structural engineering terms, concepts, subjects of concern, plus some of their derivatives all of **CRG** significance, were drilled tirelessly and repeatedly with no better intention than seeding a lasting impression in all of us

Among what were or were to be advocated, the most "sincere" point made throughout the **Series** was to form an important habit of proving any case in doubt − or even of no doubt − with "hard numbers" verified through calculation instead of playing meager rhetoric, sometimes in disdain

Every so often as we stumbled across some underworked or less exploited subject, depending on what subject of concern taken place and at what timing, who we are and how curious we are at it, etc., we might take very little or no interest in it initially, then suddenly determined to dive right down in full gear to pursuit the cold hard facts on certain subjects whether that catch popular attention or not.

"Rail Misalignment" fits to be a seriously alarming issue that worth every while of Mill Maintenance's dire attention; although to some Engineers, it could be a non-issue, a dull subject to pass on by or at best earn a trivial small talk sitting, but to us herein the most convincing means to win everybody over is by presenting the cold hard facts right here right this/next moment

To come by the cold hard facts on what could "Rail Misalignment" do to **CRG** is a tedious journey we take to feel the heat or chilliness first hand. The practical engineering way or the better way is to just run the "calculation" albeit that might bring out nothing unusual but, it could also lead to some unexpected enlightenment after all

Basically it starts out as if *the girder* is an inert entity under attack from "static" load or as in a mathematically-guided slow motion yet to start the action in full gear, but, once the calculation "cycle" gets going, we could observe closely how *the progressive rail displacement* dictates the outcome stage by stage

Cracking open the subject so deeply into the **subject of rail offset** (rail float and rail misalignment) through "numbers" should serve as perfect showing over the importance of running calculation

The intent of this **Chapter** is to establish a "very simple" database-ready specification (format) catering to **Crane Runway Girder Design Load Input Data** for engineering automation efficiency meanwhile for facilitating organized documentation purpose as well.

In a broader based context, the so-called loads/loadings of "Engineering significance" should include not only the primary $\mathbf{P_x}$ and $\mathbf{P_y}$ but also *what's beyond*, which automatically insinuates to the unavoidable **effect from rail offset measured against not the girder web but, all too real, against the true Shear Center of the girder section**.

Of numerical importance, the magnitude of $\mathbf{P_x}$ and $\mathbf{P_y}$ should have been very well configured and authenticated beforehand since the characteristics of both entities are not much different from the definition of other forms of (equipment) live load; but, to catch on with the definition and the derivation of "*what's beyond*" ordinary is never that direct.

As a whole, the subject of **effect from rail offset** beyond $\mathbf{P_x}$ and $\mathbf{P_y}$ deserves some serious delineation hereinafter, as it would take up the bulk of exposure among all areas of interest under discussion.

6.2 Defining Rail Offset (Rail Float, Rail Misalignment, etc.)

Of vital importance to **CRG's** wellbeing serving typical Mills, when focusing on the geometric setting at the rail top with respect to the extents of imperfection being quantified thereof, assortment of designations for which were established to suit diverse customs; although labels such as **rail misalignment**, **rail float**. **Rail slip** or **rail offset**, etc. were remarked in various practices, but **all** circumstances in use could be deduced collectively into:

> *The **as-measured** offset distance from an **as-observed** reference base line to the **as-displaced** centerline of the crane rail*

Each one of those rail-related terms may represent a measure of distinctive "offset" being recognized under a specific discipline and/or area of interest. Nevertheless, any confusion arising thereof could have been traced back from the variation in the definition of reference base line, however it was specified.

Depending on the interpretation being held by the controlling profession – i.e. facility fabricator, erection contractors, surveyors, inspectors, design engineers, crane operators or whatnot − a reference base line could have been, for examples:

- *An idealized theoretical centerline of the rail,*
- *A fictitious reference edge of a structural member or*
- *A component thereof,*
- *A physical building column flange or centerline or*
- *The girder web centerline,* etc.

But regardless, the orientation of measurement is taken along the **X**-direction

On being an important part of our structural analysis-design responsibility as to taking the most appropriate action on the given situation, the numerical consequence from any of these rail-related terms − no matter under what designation, what significance and of what quantities − should never be treated too lightly or being ignored

Any non-zero amount of measurement should be taken in as a regular share of our analytical-analysis-design obligation that be met earnestly; the result from which would then form the basis for providing ample strength for **CRG** to fend off the punishing elements and influences from all triggering sources combining fatigue, non-fatigue, flexural and torsion, etc.

In summarizing our perception:

Whichever ways and means an "offset" was measured, obviously, hinges upon what ***our*** *own reference base line is to begin with. Be it named rail offset, rail float, rail slip or rail misalignment is not the issue, we should accept and consolidate all designations as "****rail offset****" that has the same technical label:* $\boldsymbol{\delta_x}$

On the effect of "offset" projected onto **2-D** plane:

Once the **CRG** is placed in active service subjected to generalized loading application, if focusing on the girder responses to load at any **z**-coordinate in terms of deformations, there is always the situation of δ_y rivaling with δ_x transpired at the top of rail for our undivided attention

For practical design consideration, mathematically, neither δ_y nor δ_x have much significance in the **CRG Engineering** matter unless each individual quantity was paired up with a respective load source either P_x or P_y revolving about the **Shear Center** (**SC**) that induce a fair share of torque to be accounted for and be analyzed and designed for.

6.3 Torsional Effect Once More

CRG captures its torsion and torsional effects from applied load vector having components resolved into the orientations chosen as **X** and **Y** by user preference, thus we have:

Commonly **X**-load represents lateral thrust while **Y**-load represents vertical wheel load

Without probing much deeper,

Our "casual" understanding and impression on the implication of **CRG's** responses owing to δ_x and δ_y might be a bit ambiguous or misconceived at times

In many instances, the recognition of torsional effects owing to lateral thrust against δ_y seemed much more notorious than the effect stemmed from vertical load against δ_x, why?

Could that be its bona fide correlation with a relative **larger** torque moment arm δ_y off **Shear Center**, or perhaps by its long-standing status bestowed upon the general understanding or misunderstanding, or is it by the spur-of-the-moment perception with no solid proof?

A side note:

Debating which entity wins over on telling the genuine truth or false of an opinion in this regard is of little consequence, the more important point is, knowing the whereabouts of **shear center**

After all, **shear center** must be located on the dot; otherwise every engineering decision and conclusion could be at risk and just so we know that is the main source of garbage-in-garbage-out

Therefore don't keep speculating that the ***shear center*** *is under the crane rail*

While making elaborate calculation engaging torsional effects on the whole for the good of **CRG**,

It is quite comfortable for those unsuspected to suppose that, the influence attributed to lateral thrust P_x "seems" to win by a wide margin over the effect came from vertical wheel load P_y; albeit in some cases, it might not be an issue to concur with such a notion but not always

Conceptually, the thought being referred to might be quite justified for most **Symmetrical Sectioned CRG** if nothing else being more convincing, just take it from the snapshots of how that special *torsional moment arm* δ_y was measured from the load point, here it goes in stages:

- Start out at the rail top
- Aim in parallel with the **Y**-axis
- Aim into a shortest path towards an X-oriented line through **Shear Center**
- And during the last step whether pointing downward or upward would depend on the geometric regularity or the irregularity of the profile shape

Those snapshots had revealed only the pure static nature when focusing exclusively on δ_y's geometric definition from a static geometric point of view. Because for being a constant and it never changes, the value of δ_y stays in a steady state, thus it incites no torsion by itself until P_x comes along. The (not so) tricky part, again, is knowing where is **Shear Center** located

The messy nature of **CRG's** torsional surroundings is an established fact, but how messy it gets is still of vast interest all along, and it certainly needs to be looked into more closely. By all means it cannot be captured accurately and correctly without deliberating the dynamic interaction between P_x and P_y as we shall witness very soon

To widen up the landscape in numerical interest, we need to examine what could vertical load P_y do in response to the inherent "**rail offset**" consequential from the P_y-δ_x effect or loading position imperfection, i.e. in addition to looking at δ_y and for more fun, the sideway δ_x along the **X**-axis against the **Shear Center** should also be drawn into the picture as well

The setback if not that already time-honored:

Speaking of torsions in general terms, the effects attributed to P_y-δ_x were "hardly ever" commented or recognized *more seriously* in most **Classic Textbooks** – the most we got could be a sentence or two stating that the effect needs to be considered – or else "rarely" brought up in traditional design examples (given elsewhere) as of this writing

Of the relative short time-period of honoring P_y-δ_x effects against the long history of **CRG's** subsistence, it is only until not very long ago the subject had gotten its well-deserved recognition. Again, why is that?

- Was it true by the relatively **smaller** moment arm δ_x that P_y associates with, so it's **OK** to disregard its contribution to torsion?

- Or had the P_y-δ_x effects already been proven truly trifling by actual calculation by "someone" and compared with that from P_x-δ_y, or else just a pure hearsay?

Get a load of the truth and the hidden (or obvious) flaw if we don't mention **Shear Center**:

In relating P_x to P_y:

As long as the wheel is on the rail, P_y always presents

Yet for P_x: It is not an inborn entity as understood. Physically P_x is either not there or else if it does then, it must coexist with P_y at all times therefore one could make the statement, there would be no P_x if not for P_y

What causes the movement of $\mathbf{P_x}$ to waver toward the left and right or to come and go is all on cue from the operator's instantaneous controlling of interaction between trolley and the lifted load – dragging, striking or swinging, etc.

Maximum damage for engineering consideration:

Torsions from vertical loads and lateral thrusts were "always" in partnership with each other so long as the values of $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ and $\mathbf{P_x}$-$\boldsymbol{\delta_y}$ are non-zero

While some of the **Modern Design Guides** of late did recommend soundly that the $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ effects should be taken into account for design, but the same Guide might have failed (as of this writing) to "warn" those unwary Users/Readers about a number of important details that could be fairly critical to **CRG** design:

- Readers are to judge, is there anything wrong with establishing $\boldsymbol{\delta_x}$ by a statement such as:

  $\boldsymbol{\delta_x}$ is the "*measurement of offset dimension from the rail centerline to the girder web centerline*"

  To all outward appearances, logically, it seemed nothing out of the ordinary, yet by reading it carefully once more, we must hold some grudge and think twice about what was missing from such an unsophisticated definition; Why?

  Because there would be surprise if we don't question, and there is no surprise if we do know the reason why; the statement in general is half accurate at best yet mostly inaccurate, and the statement could only be true for those members having symmetrical section. So this brings out the victorious moment to celebrate among **simple-bending** advocates, would it?

  What would be more thoughtful in the $\boldsymbol{\delta_x}$ rationale is that, we should **always** make reference with respect to the **Shear Center** instead of the **Girder Web Centerline** for all generic applications involving members with unsymmetrical section, otherwise all hells break loose (seriously we meant under-designed)

  By all means as a reminder while we are at it, the sanction on "torsional moment arm" in all references with respect to **shear center** is equally applicable to both $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ and $\mathbf{P_x}$-$\boldsymbol{\delta_y}$ in all **CRG** applications

  Finally, if we have not made a strong-minded connection yet then, here it is again:

*The so-called "**Reference Base Line**" for measuring the rail offset for **CRG** structural engineering purpose should always be a line passing through the **Shear Center***

- One could also be surprised by a fact yet to be proven later:

  The structural behaviors from $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ whether considered independently by itself or that from a combination with $\mathbf{P_x}$-$\boldsymbol{\delta_y}$ is always *nonlinear* in nature

By and large, the combined effects due to $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ and $\mathbf{P_x}$-$\boldsymbol{\delta_y}$ cause nothing but troubles to all **CRGs** for several obvious reasons, particularly in design against metal fatigue, on account of:

- The reversible $\mathbf{P_x}$ action, which is *the culprit, even when the rail as installed was perfectly aligned with the girder web centerline and it could still induce* ± $\boldsymbol{\delta_x}$ befalling to become the torsion moment arm for $\mathbf{P_y}$

- The generic "$\mathbf{P_y}$ loading position imperfection" that became active *whenever the rail centerline* is at offset with respect to the **Shear Center**

On definition of rail offset:

Identifying what's adequate from what's inadequate is simple. But to break from doing things the wrong way into the correct way of doing "**CRG-unique** business as usual" might take some good explanation in order to win over the naysayers; or do it the better way to be more convincing is through a pre-qualified real-life numerical example with ample details.

To formalize the **shear center-based** awareness − instead of maintaining the old-fashioned but misleading classic **girder web-based** paradigm − into a new-fangled design habit does take some getting-used-to, but it shouldn't take long

From a predisposed geometric-centered point of view, with no knowledge of how and where the loads were to be applied, the good old misleading classic **girder web-based** paradigm would work *at first glance* for symmetrical sectioned or generic **I**-shaped members;

Because the **shear center** falls on or is aligned with the axis of symmetry, it might work *at first glance* but not quite so in reality

*Not just the geometry – **δx** and **δy**, i.e. – however for the torsion matter that meant to take "partial" control numerically, but the caveat is, once again, the girder web-based paradigm works only for member behaviors conform to "simple bending" thus on the surface hardly anyone would question the rationale had we accumulated the bulk of our engineering experience strictly in association with "simple bending"*

Conventionally (1) when dealing exclusively with **I**-shaped members for much too long and (2) when the newly erected/constructed structure is at its tender age not yet been battered so badly by torsion in real life, it would seem as if entirely logical to "think" that the "girder web" was in total control as if possessing the final right to be heard of in most regards

Is this a wrong conjecture or not?

All that we had mentioned on behalf of symmetrical sectioned member is all so true even beyond **I**-shaped members, but regardless, true only for members loaded through **shear center**; in simpler terms, that is only true under conditions for force $\mathbf{P_y}$ to center about the girder web, which "happens" to be collinear with the **shear center**, but not for long in real life, just read on

"Think" that is all OK when $\mathbf{P_y}$ passes through **shear center**?

Yes on the surface, and no in most cases, so think again; Readers are to figure out what happens when $\mathbf{P_x}$ came through. The bottom line, wouldn't *we agree that "**shear center**" should always be the "boss" or be the center of all torsion affairs?*

Summarizing it all, but in different words:

It does not really alleviate any of the tormenting that **CRG** underwent from torsion as mostly understood (or misunderstood) if merely by (1) humble observation of the *load-through-web-centerline* mandate or by (2) running our design application with extreme care in maintaining "vertical load passing through the girder web centerline"

So in order to get rid of torsion the only way and the impossible way, the **SRSS** load resultant must pass through the **shear center**, which is nearly impossible to come by during **CRG's** life span

If our aim is (1) to outwit the technical adversities owing to **P-δ** one giant step ahead and (2) to face the reality head on then, we should pick up a few new habits:

- Always have **shear center** in mind
- Always know where **shear center** is located (through proper calculation) and
- Always know how far off is the **shear center** from the top of the rail − along **X** and **Y**

Consideration from a load combination point of view:

$\mathbf{P_y}$-$\boldsymbol{\delta_x}$ and $\mathbf{P_x}$-$\boldsymbol{\delta_y}$ came from separate load sources against **Shear Center**, and by practical reasoning, both entities appeared **logically** independent to each other because either "effect" could mutually present or disappear – fully or partially − at spur of moment mathematically

But in reality:

$\mathbf{P_y}$ is always in the picture while $\mathbf{P_x}$ could play hide and seek on cue from crane operator's spontaneous charging. For academic purpose of calculating load magnitude, $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ and $\mathbf{P_x}$-$\boldsymbol{\delta_y}$ were independent matters if we prefer to think in that way, but they seldom act independently in real life. For no other better purposes that we kept bringing this up over and over simply because:

> Just so we know: *A number of time-honored real-life **CRG** design samples (by others) clearly had missed or miscalculated the influence from* $\mathbf{P_y}$-$\boldsymbol{\delta_x}$

The presence of $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ and $\mathbf{P_x}$-$\boldsymbol{\delta_y}$ combining (1) their more physical encountering than usual and (2) their invariable coexistence in most Mill Operation would command the two entities into full collaboration for more harm than good

Then mathematically all could be proven by calculation that $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ and ±$\mathbf{P_x}$-$\boldsymbol{\delta_y}$ would always **reciprocal** each other's favor or wrecking power, end up clutching petty aggregate damages into a collective blow − if not in a knockout fashion − to the structure far beyond normal expectancy.

As a memorable eye-witnessing experience:

It is quite noticeable as some of the more "flexible" girders would sink downward and sway sideway at the same instance as crane charges into the service bay with associated trolley in motion, *in some cases one can clearly "see" there is telltale "vibration" going on, too.*

6.4 Nonlinear Effect from Rail Offset – A Warm-up

Handling the effects due to $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ and $\mathbf{P_x}$-$\boldsymbol{\delta_y}$ incorrectly "may" or "will" cause ravaging consequence in **Open Sectioned Crane Runway Girders**; we used the quoted word "may" to downplay the fairly good chance of any unforeseeable outcome, be it good or bad.

> A similar framework of relaying a subtle caution could apply to many other classes of structure serving other industries as well, provided *all having open section profiles supporting loads of specific nature* – off **Shear Center**

As matter of fact, even without $\mathbf{P_x}$-$\boldsymbol{\delta_y}$**'s** presence – that as understood all along yet *seemed not enough said* – it can be proven by calculation that the effect out of $\mathbf{P_y}$-$\boldsymbol{\delta_x}$ alone is quite sufficient to cause great concern; therefore if not for other fleeting reasons, they both should be considered in design, no excuse.

$\mathbf{P_y} * \boldsymbol{\delta_x}$ and $\mathbf{P_x} * \boldsymbol{\delta_y}$ are **Simple Torsion Effects** based on simple multiplications determined from $\mathbf{P_y}$ times $\boldsymbol{\delta_x}$ and $\mathbf{P_x}$ times $\boldsymbol{\delta_y}$, respectively into two sets of torque values, thereby plain enough to start structural evaluation if both δ_x and δ_y were "accurately" defined; notice the quoted word "accurately"

Interestingly as would be proven beyond doubt later on, face values of $P_y * \delta_x$ and $P_x * \delta_y$ taken from the simple multiplications are **not** the adequate amount to "finalize" our calculated result, as we shall soon see what that really means

When went by normal engineering prudence:

All **CRG** structures and the component connections thereof should have been functioning **OK** if only applying the face values of $P_y * \delta_x$ and $P_x * \delta_y$ as is for engineering-design purposes, wouldn't it? Yes, as we generally believe until we explore more thoroughly

But nonetheless, things may or may not happen as generally believed in real life;

For **CRGs** with unfavorable configuration attributed to innate weakness against excessive lateral deformation and, specifically, torsion in general,

One of the fleeting but nasty elements that gradually "ruins" the structure (and there it goes with the rails, too) could be blamed on the successive nonlinear effect augmented by the initial z-rotation, which is caused mostly by the as-given values of P_y-δ_x with or without P_x-δ_y's participation

A more comprehensive treatment to the issue is established in several cases in point as follow

The *progression* of structural deformation owing to P_y-δ_x with or without P_x-δ_y is quite similar to ways how "flexible building drifts in reaction to lateral load" or "ponding of flat flexible roof caused by standing water" was illustrated.

It takes some evidence shown through calculation mimicking a slow motioned happenstance under way in order to see what is beyond **Simple Torsion** – the counterpart of **Simple Bending** so we say − from what is actually taking place.

To simplify the numerical engagement just to prove the point, we would concentrate the effort mostly on longitudinal stress, enough by which we can explore what kind of surprise there is through simple calculation.

To a typical **CRG**, the trigger action starts from a vertical concentrated load placed on the rail top subjected to "a small amount" of offset against the girder web centerline.

First the *doubly symmetric girder*:

Example 6.1

Given:

Girder shape W24X68,
Flexural and torsionally simply supported at both ends,
30 ^{ft} in length supporting crane rail of depth d_r = 6",
Rail offset dimension "e_x" from girder web coupled with single vertical load "P_y" applied at mid-span.

Required: Effect from rail offset

Solution:

P_y = Single concentrated vertical load
P_x = Lateral thrust load

e_x = Rail offset or X-eccentricity
e_y = Y-eccentricity coupled with P_x
L = Girder length = 30 ^{ft}

The key to assessing the effect from rail offset more directly and descriptively is through evaluation of longitudinal stress − shear stress is equally important but that for now is our secondary concern.

*Longitudinal stress, besides that came from (1) weak axis bending and (2) axial **Z**-load, it could be from either the (3) strong axis bending due to $\boldsymbol{P_y}$ or from the (4) $\boldsymbol{P_y}$-induced torque $\boldsymbol{T_0}$.*

T_0 = Torque moment about shear center at mid-span
= $P_y * e_x + P_x * e_y$

Being the basis for comparison, the maximum flexural bending stress due to a single concentrated vertical load could first be calculated in these steps:

M_x = Strong axis bending moment at mid-span
= P_y L / 4
= 3 P_y L $^{k-”}$
= 90 P_y

S_x = Strong axis section modulus
= 154 in^3

f_{bx} = Maximum flexural bending stress
= M_x / S_x
= 0.584 P_y ^{ksi}

It follows, one could calculate longitudinal stress owing to torque T_0 using two different methods − either by an easier but not so accurate way or by the slightly harder but more accurate way

Simplified torsional stress approach 1 − equivalent bi-moment per **Flexural Analogy**:

t_f = Flange thickness
= 0.585”

b = Flange width
= 8.965”

h = Distance between centroid of flanges
= d – t_f
= 23.73 – 0.585
= 23.145”

Simulating the application of bi-moment by resolving the torque T_0 into two equal forces into flanges at moment arm “h”;

F_{xf} = Lateral force in flange at mid-span (**Flexure Analogy**)
= T_0 / h

M_{yf} = Mid-span weak-axis bending moment in each flange
= F_{xf} L / 4

$= (T_0 / h) (L / 4)$
$= (P_y * e_x + P_x * e_y) L / 4 / h$
$= P_y e_x * (30 * 12) / 4 / 23.145$ (<u>for $P_x = 0$</u>)
$= 3.889 P_y e_x$

$S_{yf} = t_f * b^2 / 6$
$= 7.836 in^3$

$f_{bf1} = M_{yf} / S_{yf}$
$= 3.889 P_y e_x / 7.836$
$= 0.496 P_y e_x$

r_1 = Ratio of bi-moment bending stress with respect to strong-axis bending stress
$= 0.496 e_x / 0.584$
$\approx 0.85 e_x$

<u>Detailed torsional stress approach 2</u> – warping normal stress:

Ref: **Roark's** chapter for Torsion;

E = Young's modulus = 29000 ^{ksi}
G = Shear modulus = 11154 ^{ksi}
J = Torsion constant = 1.87 in^3
C_w = Warping constant = 9430 in^6

$\beta = (G J / E C_w)^{0.5}$
$= [(11154 * 1.87) / (29000 * 9430)]^{0.5}$
= 0.008733 per inch

$\beta L = 3.144$

θ = Angular rotation θ at mid-span
$= [T_o / (2 E C_w \beta^3)] * [\beta L / 2 - \tanh(\beta L / 2)]$
$= (T_o / E) [(0.5 * 3.144 – \tanh(0.5 * 3.144)] / (2 * 9430 * 0.008733^3)$
$= (T_o / E) * 0.6547 / 0.01256$
$= 52.1223 (T_o / E)$
$= 0.0018 T_o$

δ_x = Lateral deflection at rail top due to θ
$= \theta (d / 2 + d_r)$
$= 0.0018 T_o (23.73 / 2 + 6)$
$= 0.0214 T_o$
$= c T_o$ (where constant c = 0.0214)
$= 0.0214 P_y e_x$ (<u>for $P_x = 0$</u>)

An important note:

The subsequent analysis and study is irrelevant if using <u>simplified torsional stress approach 1</u>

θ'' = Second derivative of angular rotation θ at mid-span
$= [T_o / (2 E C_w \beta)] * \tanh(\beta L / 2)$
$= 0.00557 (P_y e_x / E)$

ω_n = Normalized warping constant
$= 51.9$

σ_n = Warping normal stress
= θ'' E ω_n , or
= θ'' E (h b / 4)
= 0.00557 (P_y e_x) * 23.145 * 8.965 / 4
= 0.29 P_y e_x

At this point, someone may suggest an idea why not using the *Warping Moment* or the so-called *Bi-moment* $\mathbf{M_{zw}}$ to calculate warping normal stress as we "know" the formula $\boldsymbol{\sigma_n = M_{zw}\ \omega_n\ /\ C_w}$ and wouldn't that be much easier?

A good question, interestingly if someone actually did bring it up; but the answer could be yes and also no, too

Yes, we sure can use $\mathbf{M_{zw}}$ but only if we were given its exact value "already" calculated ahead of time; in this case what is the value of bi-moment $\mathbf{M_{zw}}$ at the mid-span is the question. Remember $\boldsymbol{M_{zw} = \theta'' E C_w}$ where $\boldsymbol{\theta''}$ is the calculated value at mid-span

The "problem" is we have to know $\boldsymbol{\theta''}$ **first** before we know what $\mathbf{M_{zw}}$ is. It's a long process to have that; we need to (1) find out what is the continuous function $\boldsymbol{\theta}$ first, (2) work out its second derivative $\boldsymbol{\theta''}$, (3) plug in Z = L / 2 to $\boldsymbol{\theta''}$ in order to arrive at $\mathbf{M_{zw}}$

So we know the true answer: Theoretically yes but practically no for this example problem. The logic is, once we have $\boldsymbol{\theta''}$ but then, why do we still need to bother with $\mathbf{M_{zw}}$ if the only goal is to figure out $\boldsymbol{\sigma_n}$ other than for **R&D** studying purpose, makes sense?

r_2 = Ratio of warping normal stress to strong-axis bending stress
= 0.29 e_x / 0.584
$\approx$ 0.5 e_x

Approach 1 was favored by many Engineers for several reasons:

Apparently, the going through with approach 2 engaging hyperbolic functions is more strenuous than what it takes per approach 1, which should be the reason #1 why it was more favored over approach 2 in (most) practices and in (many) Textbooks also

But herein with the quantity of "$\mathbf{P_y}$" being a constant, the stress comparison ratio $\mathbf{r_1}$ = 0.85 $\mathbf{e_x}$ is noticeably so much more conservative than $\mathbf{r_2}$ = 0.5 $\mathbf{e_x}$. If nothing else affecting, for instance, the fabrication-construction budget, and don't mind the design being overly conservative – *as far as longitudinal stress is concerned* − then, that should be the reason #2 why approach 1 was favored more frequently than approach 2 from that perspective

After all, the **CRG** design engineer in charge has to weight in on what price to pay from taking it easy or spending minimum effort on the technical side and/or for being too conservative:

When qualifying **non-CRG** structures if the fiber stress was calculated per simplified approach 1 then the stress ratio 0.85 $\mathbf{e_x}$ in this case might be too high for good reason;

What 0.85 − relatively close to 1.00 − means is the magnitude of warping normal stress is catching up with that of strong axis bending stress

That may be **OK** in the short term or halfway done with the calculation, but it may have seeded the potential of an overstressed situation when time comes

But what does it really mean by when time comes?

The answer is when time comes to evaluate certain critical components' strength against metal fatigue

No matter being **OK** or not, the situation might be salvaged using approach 2 given the ratio 0.5 $\mathbf{e_x}$ as a design margin leeway. Yet again, this scheme is applicable to some of the girders with symmetrical profile for the benefit of reducing fiber stress owing to torsion. But even so but don't forget, *there is no guarantee on the numerical accuracy when figuring the shear stress combining the effects from both flexure and torsion*

But how conservative we want it to be?

In the **Example**, the fiber stress owing to torsion per approach 1 is "unofficially" at a whopping 70% (= 0.85 / 0.5 – 1) more conservative than given by approach 2, that is indeed **too conservative** if not considered unrealistic

We Engineers need to be aware of the pros and cons of what we do; there is a hefty price to pay in both the material and fabrication cost from being overly conservative

Potential issue:

Some Readers may have noticed (if not that obvious) that something was missing from the simplified approach 1: (1) the angular rotation ($\boldsymbol{\theta_z}$) at mid-span, and correspondingly (2) the mid-span lateral deflection ($\boldsymbol{\delta_x}$) at the rail top

That is because there isn't any practical measure for justifying the accuracy and the rationale of θ_z *and* $\boldsymbol{\delta_x}$ *if we look at things only through* ***Flexural Analogy*** *unless doing it the genuine torsional way, we meant by the detailed torsional approach 2* as demonstrated

What is the obvious problem with **Flexural Analogy**? Take it here for instance:

- *The calculation for both lateral and vertical deflections would be inaccurate without a reasonable fix of rotation* θ_z *to begin with, and thereby the evaluation for deflection (or serviceability) would be bogus*

- *While that being a serious issue and although not specifically dealt with herein with much detail, but the definition of torsional shear flow especially for unsymmetrical sectioned members would become unrealistic or downright questionable, and thus the shear stress calculation would also be inaccurate*

  Needless to say it out loud, but the evaluation for non-fatigue based shear stress and fatigue shear stress reversal would be bogus, too

Basically we are cheating ourselves (and our Clients) thinking it is **OK** by using **Flexure Analogy** to qualify the adequacy of **CRG**.

6.5 Rail Offset Reality Factor – The Definition

The expression, ***reality factor****, if it appeared elsewhere then it must be for different subjects for other purposes and should mean something else.*

Herein only of **CRG**'s specific interest, The so-called **reality factor** is simply the ratio taken between the *progressively accumulated final amount of lateral deflection* and the *initial static amount of lateral deflection* of the structure in response to applied torsion

The terminology is newly introduced in this **Article Series** and it deserves some clarification and further definition from here and on.

We would continue further with the sample **Example 6.1** as follow, this exercise seemed as if we were sidetracking away from the main focus, yet it is anything but.

Getting back at detailed torsional approach 2 over the subject of lateral deflection at the rail top

Recalling from **Example, 6.1** there we have,

θ = Angular rotation θ at mid-span
$= [T_o / (2 E C_w \beta^3)] * [\beta L / 2 - \tanh(\beta L / 2)]$

δ_x = Lateral deflection at rail top due to θ
$= \theta (d / 2 + d_r)$
$= [T_o / (2 E C_w \beta^3)] * [\beta L / 2 - \tanh(\beta L / 2)] * (d / 2 + d_r)$
$= \mathbf{c\ T_o}$

Given the value of **E, $\mathbf{C_w}$, $\boldsymbol{\beta}$, L, d** and $\mathbf{d_r}$, we arrived at $\boldsymbol{\delta_x} = \mathbf{c\ T_o}$

Since torsion can be induced by both $\mathbf{P_y}$ and $\mathbf{P_x}$ simultaneously, we see what is all about the expression $\boldsymbol{\delta_x} = \mathbf{c\ T_o}$ when expanding the $\mathbf{T_o}$ term into a more generalized form:

$\delta_x = c\ (P_y * e_x + P_x * e_y)$

For convenience in deducing down to the bottom of our next intent:

Let $\boldsymbol{\delta_{x0}}$ be the **X**-displacement due to initial eccentricity $\mathbf{e_{x0}}$,

$\mathbf{e_y}$ is the distance measured from the top of rail either downward or upward towards the **Shear Center** – may or may have *nothing to do with the web centerline* – which is a fixed measurement,

Thus $\mathbf{e_y}$ always stays being constant (that does not change with the $\mathbf{P_y}$ load application,) we now replace e_x with $\mathbf{e_{x0}}$ and have:

$\delta_{x0} = c\ (P_y * e_{x0} + P_x * e_y)$

If there is (1) no inherent rail misalignment load and (2) no force acting at all as $\mathbf{P_y} = \mathbf{P_x} = 0$ then naturally $\boldsymbol{\delta_{x0}} = 0$, otherwise $\boldsymbol{\delta_{x0}}$ would always be a non-trivial quantity as soon as a non-zero $\mathbf{P_y}$ is coupled with a non-trivial x-oriented deformation $\mathbf{e_{x0}}$ regardless to what value of $\mathbf{P_x}$

And then soon after $\boldsymbol{\delta_{x0}}$ joins in, it adds to the initial eccentricity $\mathbf{e_{x0}}$, by which as a result the "most current" deflection becomes $\mathbf{e_{x1}} = \mathbf{e_{x0}} + \boldsymbol{\delta_{x0}}$ that in turn would have:

- Increased the torsional moment arm along the **X**-axis and
- Furthered the lateral deflection due to non-zero $\mathbf{P_y}$ against a new torsional moment arm $\mathbf{e_{x1}}$

As in the next expressions:

$\delta_{x1} = c\ (P_y * e_{x1} + P_x * e_y)$

$= c\ [(P_y * (e_{x0} + \delta_{x0}) + P_x * e_y]$

Herein the subscript ($_{0}$) represents the initial cycle **#0** while the incremental subscript ($_{1}$) designates the subsequent cycle **#1**

> *And at this "early" stage we are barely starting at cycle **#0**, for certain the numerical value of the freshly induced deflection* $\boldsymbol{\delta_{x1}}$ *resulting from application of* ($\boldsymbol{e_{x0} + \delta_{x0}}$) *has very little chance to be identical to its triggering eccentricity*

By means of which, knowing ($\mathbf{e_{x0}} + \boldsymbol{\delta}_{\mathbf{x0}}$) $\neq \boldsymbol{\delta}_{\mathbf{x1}}$ and therefore, the lateral movement in progress must go into the next cycle **#2** rendering a new $\boldsymbol{\delta}_{\mathbf{x2}}$

By further comparison:

If the value of $\boldsymbol{\delta}_{\mathbf{x2}}$ does not come close enough to be ($\mathbf{e_{x0}} + \boldsymbol{\delta}_{\mathbf{x1}}$) signaling a convergence has not been reached then, it would continue on with the next cycle **#3** … until it finally converges at cycle **#n**, from which the final displacement $\boldsymbol{\delta}_{\mathbf{xn}} \approx (\mathbf{e_{x0}} + \boldsymbol{\delta}_{\mathbf{x,n-1}})$ and the "iteration" process went by something like this:

$\delta_{x2} = c\ [(P_y * (e_{x0} + \delta_{x1}) + P_x * e_y]$
$\delta_{x3} = c\ [(P_y * (e_{x0} + \delta_{x2}) + P_x * e_y]$
…
$\delta_{xn} = c\ [(P_y * (e_{x0} + \delta_{x,n-1}) + P_x * e_y]$
$\approx \delta_{x,n-1}$

With **c** = 0.0214 – see **Example 6.1**, Detailed torsional stress approach 2 – for our sample girder, the process could be demonstrated via a series of numerical *definition-redefinition* using various parameters of interest, here we start out with:

Case 1:

By letting $\mathbf{P_y}$ = 10 ^{kips}, $\mathbf{e_{x0}}$ = 0.5" and $\mathbf{P_x} * \mathbf{e_y}$ = 0 then:

$\delta_{x1} = 0.0214 * 10 * 0.5 = 0.107$
$\delta_{x2} = 0.0214 * 10 * (0.5 + 0.107) = 0.1299$
$\delta_{x3} = 0.0214 * 10 * (0.5 + 0.1299) = 0.1348$
$\delta_{x4} = 0.0214 * 10 * (0.5 + 0.1348) = 0.1358$
$\delta_{x5} = 0.0214 * 10 * (0.5 + 0.1358) = 0.1361$
$\delta_{x6} = 0.0214 * 10 * (0.5 + 0.1361) = 0.1361$
$\approx \delta_{x5}$

Remember way back in **Chapter 2** under the section of "**How is CRG Loaded**" in which we did mention that this is a "**nonlinear event**"

Finally via progression from $\boldsymbol{\delta}_{\mathbf{x1}}$ to $\boldsymbol{\delta}_{\mathbf{x6}}$, it proved it is indeed a non-linear progression. Interestingly the ratio of the final rail offset at convergence against the initial rail offset becomes:

$(\boldsymbol{\delta}_{\mathbf{x6}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}} = (0.5 + 0.1361) / 0.5$
$= \mathbf{0.6361} / 0.5$
$= 1.2702$

The specific fact as exemplified in this case:

n = 6 cycles,
At convergence $(\boldsymbol{\delta}_{\mathbf{x6}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}} = 1.2702$

From this vantage point, we see that numerically $(\boldsymbol{\delta_{xn}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}}$ is simply the ratio of *final* **steady-state** lateral displacement over the *initial* **transient-state** lateral displacement

To extrapolate such awareness more generically based on the combination of (1) final "n" number of cycles and (2) the final magnitude of $(\boldsymbol{\delta_{xn}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}}$, it should lead us into a qualitative insight indicating how strong the girder really is for it to resist excessive lateral movement

The morale:

Given a value of $\mathbf{e_{x0}}$ = 0.5" is only the beginning. And "normally" that is not good enough to tell the full story behind or what the "reality" we are in for − until we see that the final sum of $\boldsymbol{\delta_{x6}} + \mathbf{e_{x0}}$ = **0.6361**"

Thereby one could readily identify $(\boldsymbol{\delta_{xn}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}}$ as some sort of "**Reality Factor**" or name that anything else whichever being more meaningful; nevertheless, the biggest surprise out of this is the 27% increase from the initial amount, and that should call to our attention to solicit some educated opinion or judgment:

Anyone surprised?
Does 27% seem (not) recognizable?
Is it too much, or not at all?
Can we call it secondary effect or something negligible?

Regardless to (1) whichever design criteria we've been "accepting" to observe in design or (2) how familiar we were with the subject of rail misalignment prior to the latest finding as demonstrated, but how about viewing the "**reality factor**" from a different perspective:

The initial (arbitrarily given) lateral offset known to be $\mathbf{e_{x0}}$ = 0.5", which, by calculation, happens to be exactly **L** / 720 for a 30^{ft} girder;

It doesn't matter calling it a coincidence or pure luck. And that **might have been acceptable** on paper provided that the lateral deflection tolerance limit is set (per a certain design criteria) at, say **L** / 600 – if only *considering rigid-body **X**-deflection, i.e. no consideration of rotation about **Z**-axis* (through the **Shear Center**)

However, the condition may only be "acceptable" before we ran the number per detailed torsional approach 2, and for the moment, short of being confused, some of the Engineers may need to think twice; where should we go from here?

If looking into the circumstance a bit more seriously than it appears:

- For the final rail offset converged at 0.6361", which comes up to about **L** / 566.

  Knowing that **L** / 566 > **L** / 600:

  Does it mean that -

  - *The Crane Wheel, or*
  - *The Crane Railhead, or*
  - *The Girder itself, or*
  - *Even the Lateral Thrust Tie-back Connection or*
  - *The Girder Seat Bolts, or*
  - *The Support Building Column, or*
  - *The Crane Column, etc.,*

  *Is/are seeing more pseudo-dynamic action than it was to be blessed for pertaining to **L** / 600?*

- On the lighter side if we make an excuse, that shouldn't constitute a serious design violation other than a little bit of numerical out of bound based on <u>**L** / 566 > **L** / 600</u>

  But from the outcome of approach 1 (**Flexural Analogy**) we see if someone insists on being conservative and doing it the equivocal way, however and whatever it may develop, then the final rail offset would have far exceeded **L** / 566 as well as the sacred limit of **L** / 600 by a much wider margin

- By straight proportion, the original stress comparison ratio $\mathbf{r_1}$ = 0.85 $\mathbf{e_x}$ (per approach 1) would be 1.27 * 0.85 $\mathbf{e_x}$ = 1.0795 $\mathbf{e_x}$ while the original $\mathbf{r_2}$ = 0.5 $\mathbf{e_x}$ (per approach 2) would become 1.27 * 0.5 $\mathbf{e_x}$ = 0.635 $\mathbf{e_x}$

  Apparently besides the serviceability issue yet to be addressed herein, there could also be a serious overstress problem threatening over by the extra 27% from rail offset in addition to the non-linear displacement as demonstrated

In summary once again, what being exposed here would not have been discovered that easily or never will if we went straight with **simplified torsional stress approach 1.**

Now onto the serviceability issue, which we must tackle sooner or later; there are some interesting questions and answers for girder design consideration.

> There is a need to go much deeper into the subject of serviceability, and now, knowing what **reality factor** can play an important part, but how? It would not be meaningful unless our provisions of **Q&A** on all aspects were complete and made sense
>
> Normally we would have solemnly observed the sacred design criteria mandating, for instance, **L** / 600 as the absolute final lateral offset limit for sake of protecting the Cranes, girders and the Crane Rails, etc.; and that's the end of it
>
> > But, owing to the 1.27 **reality factor** as demonstrated, then instead of enforcing a well-publicized [**L** / 600] value, the question now becomes:
> >
> > *Shall we enforce a more stringent deflection limit of **L** / 762 (= **L** / 600 / 1.27) to begin with, and set it as part of our own design criteria, wouldn't that be more realistic?*
>
> Or reasoning from a more proactive position,
>
> > *The Industry at large may put in an entreated limit of **L** / 600 as an Engineering design goal to meet or so not to exceed during service,*
> >
> > > *But we, the Structural Engineers, should in reality aim for **L** / 762 (based on the sample calculation) as if that is our hidden/exposed design goal*
> >
> > *Does that make better engineering sense?*
>
> <u>Or should we (or not) go one step further</u>:
>
> > Judging any in-use value of deflection limit as being practical or not is a different argument, but to extrapolate from the as-given "**L** over whatever number" as the deflection limit
> >
> > > Be it 600, 800 or 1000, etc.

Shall we, the design engineers in charge, shoot for the "product" of whichever that number is times the **conjured reality factor** of 1.27 so that 600 would become 762 and 1000 would become 1270 instead?

If this line of attack so far based only on $\mathbf{P_y}$-$\mathbf{\delta_x}$ makes practical sense (in absence of $\mathbf{P_x}$-$\mathbf{\delta_y}$) thus far then, one may wonder would it get any better or worse from digging it even deeper than we just did; here are some further questions to get it going:

*How "realistic" is the **reality factor**?*
Is it a fixed constant or case-dependent?
Could it be affected greatly with presence of $\mathbf{P_x}$-$\mathbf{\delta_y}$?
.....

6.6 Rail Offset Reality Factor – The Reality

Continuing with **Example 6.1**,

(Readers may need working back to the original problem definition to avoid misunderstanding of the intent) herein we will explore into the "reality" through a few more cases to appreciate what "reality" we've been overlooking for so long:

Case 2:

If carrying on with $\mathbf{P_y} = 10^{\text{kips}}$ and $\mathbf{P_x} * \mathbf{e_y} = 0$ but with an increased initial $\mathbf{e_{x0}}$ = 1" (instead of 0.5") then:

$\delta_{x1} = 0.0214 * 10 * 1 = 0.214$
$\delta_{x2} = 0.0214 * 10 * (1 + 0.214) = 0.2598$
$\delta_{x3} = 0.0214 * 10 * (1 + 0.2598) = 0.2696$
…
$\delta_{x6} = 0.0214 * 10 * (1 + 0.2721) = 0.2722$
$\delta_{x7} = 0.0214 * 10 * (1 + 0.2722) = 0.2722$
$\approx \delta_{x6}$

It takes n = 7 cycles to converge for $\mathbf{e_{x0}}$ = 1" – instead of 6 cycles for $\mathbf{e_{x0}}$ = 0.5"

And the ratio of the final rail offset at convergence with respect to the initial rail offset = $(\mathbf{\delta_{x7}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}}$ = 1.2722 / 1.0 = 1.2722, which remains at about 27% over the initial offset amount

A coincidence or not is what we need to find out

Case 3:

Let's see what happens if still keeping $\mathbf{P_y} = 10^{\text{kips}}$ and $\mathbf{P_x} * \mathbf{e_y} = 0$ but increasing the initial rail misalignment to $\mathbf{e_{x0}}$ = 2" then:

$\delta_{x1} = 0.0214 * 10 * 2 = 0.428$
$\delta_{x2} = 0.0214 * 10 * (2 + 0.428) = 0.5196$
$\delta_{x3} = 0.0214 * 10 * (2 + 0.5196) = 0.53919$
…
$\delta_{x7} = 0.0214 * 10 * (2 + 0.54448) = 0.544518$
$\delta_{x8} = 0.0214 * 10 * (2 + 0.544518) = 0.544526$
$\approx \delta_{x7}$

Apparently, it required greater number of cycles (**n** = 8) in order to reach convergence as we increase from a smaller initial offset to a much greater value.

> In this particular case, the ratio of final rail offset at convergence with respect to the initial rail offset = $(\boldsymbol{\delta_{x8}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}}$ = 2.544526 / 2 = 1.2723, which is still very close to the magical 27%.

The percentage had increased a bit but not by much as we bumped up the initial offset value substantially in the current case ($\mathbf{e_{x0}}$ = 2") over that as given in case 1 ($\mathbf{e_{x0}}$ = 0.5") but should reach a numerical plateau at about 1.2723 (for the sample girder.)

Case 4:

Keeping the original $\mathbf{e_{x0}}$ = 0.5 and $\mathbf{P_y}$ =10 ^{kips} but letting in the participation from lateral load at only 10% of the vertical load; $\mathbf{P_x}$ = 10% * $\mathbf{P_y}$ = 1 ^{kips}

δ_{x1} = 0.0214 * [P_y * (e_0 + 0) + P_x * e_y]
= 0.0214 * [10 * (e_0 + 0) + 1 * 17.865]
= 0.0214 * [10 * (0.5 + 0) + 17.865] = 0.4891 <<- initial offset

δ_{x2} = 0.0214 * [10 * (0.5 + 0.4891) + 17.865] = 0.594
δ_{x3} = 0.0214 * [10 * (0.5 + 0.594) + 17.865] = 0.6162
…
δ_{x6} = 0.0214 * [10 * (0.5 + 0.622201) + 17.865] = 0.62223
δ_{x7} = 0.0214 * [10 * (0.5 + 0. 62223) + 17.865] = 0.62228
δ_{x8} = 0.0214 * [10 * (0.5 + 0.62228) + 17.865] = 0.62229
$\approx \delta_{x7}$

It's either "all academic" or "pure imagination" but there could be two different scenarios of initial rail offset at play here, which should and would have influenced over how we interpret the ratio of the final rail offset at convergence:

- Considering two different scenarios: (1) both $\mathbf{P_y}$ and $\mathbf{P_x}$ are simultaneously acting with no timing gap in between and (2) treating $\mathbf{e_{x1}}$ as part of the initial offset, therefore:

  $(\boldsymbol{\delta_{x8}} + \mathbf{e_{x0}}) / (\mathbf{e_{x1}} + \mathbf{e_{x0}})$ = (0.62229 + 0.5) / (0.4891 + 0.5)
  = 1.135

  If taking the calculated relative magnitude against the normalized value of 1.0 by straight comparison then, the 1.135 displacement ratio may appear deceivingly low, but, how about evaluating the total displacement (0.62229 + 0.5) = 1.12229" on a fictitious 30-ft long girder (or that comes to **L** / 321)?

  Isn't (**L** / 321) "**alarmingly**" high?

And just be more realistic if that happens; *the girder may still be standing but the rail or the rail clip(s) may have been seriously torn, meanwhile what about the crane?*

- Consider $\mathbf{P_y}$ was acting all alone by itself long before $\mathbf{P_x}$ joined in, and so:

  $(\boldsymbol{\delta_{x8}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}}$ = (0.62229 + 0.5) / 0.5
  = 2.245

There is no need to figure out **L** / (whatever) but no doubt about it, 2.245 is way too much over 1.0 by any standard

Case 5:

Same as for Case 4 with both $\mathbf{P_y}$ and $\mathbf{P_x}$ present, but letting $\mathbf{e_{x0}} = 0$ to simulate the condition of a perfectly aligned rail:

$\delta_{x1} = 0.0214 * [P_y * (e_0 + \delta_{x1}) + P_x * e_y]$
$= 0.0214 * [10 * (0 + 0) + 17.865] \quad = 0.382311$

$\delta_{x2} = 0.0214 * [10 * (0 + 0.382311) + 17.865] = 0.464126$
$\delta_{x3} = 0.0214 * [10 * (0 + 0.464126) + 17.865] = 0.481634$
…
$\delta_{x6} = 0.0214 * [10 * (0 + 0.486182) + 17.865] = 0.486354$
$\delta_{x7} = 0.0214 * [10 * (0 + 0.486354) + 17.865] = 0.486391$
$\delta_{x8} = 0.0214 * [10 * (0 + 0.486391) + 17.865] = 0.486399$
$\approx \delta_{x7}$

Since $\mathbf{e_0} = 0$ so naturally we would consider $\boldsymbol{\delta_{x1}}$ as the initial offset,

The ratio of the final rail offset at convergence to the initial rail offset = $(\boldsymbol{\delta_{x8}} + \mathbf{e_{x0}}) / \boldsymbol{\delta_{x1}}$ = $(0.486399 + 0) / 0.382311 = 1.272$.

Surprisingly it's 27% once again as if some magic number for this particular girder

Depending on what tool is employed in studying our/your rudimentary nonlinear rail-float progression as demonstrated, for certain, the results from punching calculator should only be slightly different from that using automated routine to crank out numbers in double-precision; **but, the results from Case 4 and Case 5 should have been the best testimony to the reality that $\mathbf{P_y}$ and $\mathbf{P_x}$ would always enhance each other's wrecking power regardless if $\mathbf{e_{x0} = 0}$ or not.**

What about girder with fixed ends?

Example 6.2

Given:

Same girder and identical loading parameters as given in **Example 6.1** except that both ends are fixed both in flexural and torsional senses.

Required: Effect from rail offset

Solution:

P_y = Single concentrated vertical load
e_x = Rail offset
L = Girder length = 30 ^{ft}
$T_0 = P\ e_x$

At both support ends and at mid-span, now calculate the maximum flexural bending stress from the concentrated vertical load "P" resulting into a value exactly one half of that for **Example 6.1**:

f_{bx} = Maximum flexural bending stress
$= 0.584\ P_y / 2$
$= 0.292\ P^{\ ksi}$

Simplified torsional stress approach 1 − equivalent bi-moment using **flexure analogy**:

$f_{bf1} = 0.496\ P_y\ e_x / 2$
$= 0.248\ P_y\ e_x$

r_1 = Ratio of bi-moment bending stress to strong-axis bending stress
$= 0.248\ e_x / 0.292$
$\approx 0.85\ e_x$

Detailed torsional stress approach 2 – warping normal stress:

Ref: **Roark's** chapter for Torsion;

C_w = Warping constant = 9430 in^6
β = 0.008733 per inch
βL = 3.144

θ = Angular rotation θ at mid-span
$= [T_o / (E\ C_w\ \beta^3)] * [\beta L / 4 - \tanh(\beta L / 4)]$
$= (T_o / E)\ [(0.25 * 3.144 – \tanh(0.25 * 3.144)] / (9430 * 0.008733^3)$
$= (T_o / E) * 0.12986 / 0.006281$
$= 20.6755\ (T_o / E)$
$= 0.000713\ T_o$

δ_x = Lateral deflection at rail top due to θ
$= \theta\ (d / 2 + d_r)$
$= 0.000713\ T_o\ (23.73 / 2 + 6)$
$= 0.0127\ T_o$
$= c\ T_o$ (where constant c = 0.0127)
$= 0.0127\ P_y\ e_x$ (for $P_x = 0$)

Similar to Case 1 of **Example 6.1** by letting $\mathbf{P_y} = 10^{kips}$, $\mathbf{e_{x0}}$ = 0.5" and $\mathbf{P_x} * \mathbf{e_y} = 0$ then:

$\delta_{x1} = 0.0127 * 10 * 0.5 = 0.0635$
$\delta_{x2} = 0.0127 * 10 * (0.5 + 0.0635) = 0.07156$
$\delta_{x3} = 0.0127 * 10 * (0.5 + 0.07156) = 0.07259$
$\delta_{x4} = 0.0127 * 10 * (0.5 + 0.07259) = 0.07272$
$\delta_{x5} = 0.0127 * 10 * (0.5 + 0.07272) = 0.07274$
$\approx \delta_{x4}$

The ratio of final rail offset to initial rail offset:

$(\boldsymbol{\delta_{x5}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}} = (0.5 + 0.\ 07274) / 0.5$
$= 1.1455$

It ended up about 15% increase from the initial amount, which is roughly half of that for simply supported girder, or grew from the given $\mathbf{e_{x0}}$ = 0.5" = **L** / 720 for a 30^{ft} girder into $(\boldsymbol{\delta_{x5}} + \mathbf{e_{x0}})$ = (0.5 + 0. 07274) = **L** / 629.

θ'' = Second derivative of angular rotation θ at mid-span
$= [T_o / (2\ E\ C_w\ \beta)] * \tanh(\beta\ L / 4)$
$= 0.00398\ (P_y\ e_x / E)$

ω_n = Normalized warping constant = 51.9^{ksi}
σ_n = Warping normal stress
$= \theta''\ E\ \omega_n$, or

$= 0.00398 (P_y e_x) * 51.9$
$= 0.207 P_y e_x$

r_2 = Ratio of warping normal stress to strong-axis bending stress
$= 0.207 e_x / 0.292$
$\approx 0.71 e_x$

In this case the result from approach 1 is only 20% (= 0.85 / 0.71 – 1) more conservative than that obtained from approach 2.

What about unsymmetrical sectioned girders?

Example 6.3

Given:

A composite girder W21X55 with side channel C8X11.5 by attaching the C8 flange to the web of W21 at 2.35" below the top flange of W21. Flexural and torsionally simply supported both ends, 20 ^{ft} long, given rail offset "e_x" from web of W21, single crane load "P_y" applied at mid-span.

Required: Effect from applied rail offset

Solution:

P_y = Single concentrated vertical load

x_0 = **Shear center** offset from the web of W21
= 0.17" on the C8 side

y_0 = Measured from **shear center** to top of top flange
= 5.0428"

$(e_x \pm x_0)$ = Rail offset
L = girder length = 20 ^{ft}

T_0 = Torque moment about shear center due to vertical load at mid-span
$= P_y (e_x \pm x_0)$

Based on the cross section properties worked out with respect to principal axes (calculation details omitted here,) apparently the maximum bending stress occurs at one of the bottom flange tips

Calculate the maximum flexural bending stress from concentrated vertical load:

M_x = Strong axis bending moment at mid-span
$= P_y L / 4$
$= 3 P_y L^{k-"}$
$= 60 P_y$

S_x = Strong axis section modulus
$= 118.66 \text{ in}^3$

f_{bx} = Maximum flexural bending stress
$= M_x / S_x$
$= 0.506 P_y^{\ ksi}$

Simplified approach 1 - equivalent bi-moment by **flexure analogy**:

t_f = Flange thickness
= 0.52"

h = Distance between centroid of flanges
$= d - t_f$
= 20.8 – 0.52
= 20.28"

b = Flange width
= 8.4"

F_{xf} = Lateral force in flange at mid-span
$= T_0 / h$

M_{yf} = Mid-span weak-axis bending moment in each flange
$= F_{xf} L / 4$
$= (T_0 / h) (L / 4)$
$= P_y (e_x \pm x_0) * 20 * 12 / 4 / 20.28$
$= 2.959 P_y (e_x \pm x_0)$

$S_{yf} = t_f * b^2 / 6$
$= 6.115 in^3$

$f_{bf1} = M_{yf} / S_{yf}$
$= 2.959 P_y (e_x \pm x_0) / 6.115$
$= 0.484 P_y (e_x \pm x_0)$

r_1 = Ratio of bi-moment bending stress to strong-axis bending stress
$= 0.484 (e_x \pm x_0) / 0.506$
$\approx 0.957 (e_x \pm x_0)$

Approach 2 – warping normal stress:

Ref: **Roark's** chapter for Torsion;

E = Young's modulus = 29000 ^{ksi}
G = Shear modulus = 11154 ^{ksi}
J = torsion constant = 1.37 in^3
C_w = warping constant = 7572 in^6

$\beta = (G J / E C_w)^{0.5}$
$= [(11154 * 1.37) / (29000 * 7572)]^{0.5}$
= 0.00834 per inch

$\beta L = 2$ for $L = 20^{ft}$

θ = Angular rotation θ at mid-span
$= [T_o / (2 E C_w \beta^3)] * [\beta L / 2 - \tanh(\beta L / 2)]$
$= (T_o / E) [(0.5 * 2 - \tanh(0.5 * 2)] / (2 * 7572 * 0.00834^3)$
$= (T_o / E) * 0.2384 / 0.008785$
$= 27.137 (T_o / E)$
$= 0.0009358 T_o$

δ_x = Lateral deflection at rail top due to θ

$= \theta\,(y_0 + d_r)$
$= 0.\,0009358\ T_o\,(5.0428 + 6)$
$= c\ T_o$ (where constant c = 0.0009358)
$= 0.01033\ T_o$

If by letting $\mathbf{P_y} = 10^{\text{ kips}}$, $\mathbf{e_{x0}} = 0.5$" and $\mathbf{P_x} * \mathbf{e_y} = 0$ then:

$\delta_{x1} = 0.01033 * 10 * 0.5 = 0.05165$
$\delta_{x2} = 0.01033 * 10 * (0.5 + 0.05165) = 0.05699$
$\delta_{x3} = 0.01033 * 10 * (0.5 + 0.05699) = 0.05754$
$\delta_{x4} = 0.01033 * 10 * (0.5 + 0.05754) = 0.05759$
$\delta_{x5} = 0.01033 * 10 * (0.5 + 0.05759) = 0.05760$
$\approx \delta_{x4}$

The ratio of the final rail offset at convergence to the initial rail offset:

$$(\boldsymbol{\delta_{x5}} + \mathbf{e_{x0}}) / \mathbf{e_{x0}} = (0.5 + 0.\,0576) / 0.5 = 1.115$$

θ'' = Second derivative of angular rotation θ at mid-span
$= [T_o / (2\ E\ C_w\ \beta)] * \tanh(\beta\ L / 2)$
$= 0.00603\ P_y\,(e_x \pm x_0) / E$

ω_n = Normalized warping constant = $64^{\text{ ksi}}$
σ_n = Warping normal stress
$= \theta''\ E\ \omega_n$
$= 0.00603\ P_y\,(e_x \pm x_0) * 64$
$= 0.386\ P_y\,(e_x \pm x_0)$

r_2 = Ratio of warping normal stress to strong-axis bending stress
$= 0.386\,(e_x \pm x_0)\ / 0.506$
$\approx 0.763\,(e_x \pm x_0)$

By keeping "$\mathbf{P_y\,(e_x \pm x_0)}$" as constant, the stress comparison ratio from approach 1 (= 0.957) is now only about 25% more conservative than that from using approach 2 = (0.763.)

Depending on whether the sign being carried by rail offset is positive or negative relative to the **shear center**, it can either enhance or cancel out the effect to a certain degree − just so we are aware of the fact.

But by limiting a 0.03"/ft offset ratio, the design offset for a 20 ft girder would become 0.03 * 20 ± $\mathbf{x_0}$ = 0.6 ± 0.17 = 0.77" or 0.43". Using approach 2, the warping normal stress would become 0.297 $\mathbf{P_y}$ or 0.156 $\mathbf{P_y}$, which correspondingly is in between the 60% and 33% of the stress due to strong-axis bending. The ratio would even be much higher if using approach 1.

6.7 Rail Offset Reality Factor – The Implication

Following along with the calculation as demonstrated from **Example 6.1** through **Example 6.3** with focus on the longitudinal stress and lateral deflection, several subtle conclusions could be drawn from the study:

(a) Knowing the results as analyzed for a typical symmetrical sectioned member devoid of warping-related restraining effect per approach 1 – **Flexural Analogy** – therewith although is generally more conservative than the results from using approach 2, one can conclude that, it would be way too conservative for – although rarely used scheme − doubly symmetric girders especially if the ends were simply supported.

Besides that, there remain unresolved issues in approach 1 regarding the evaluation for *serviceability and shear stresses*.

(b) Looking back, based on results taken from the majority of cases already established on lateral deflection calculation, wouldn't we notice that it inadvertently led us through a hidden door into another engineering wonderland that needs to be explored further?

- The upper bound ratio (**reality factor**) of final offset at convergence over the initial offset may range between 27% and, say a <u>guesstimated</u> upper bound of 30% (i.e. more or less by pure **guessing**) for simply supported members, and those values may probably be reduced in half for members with fixed end conditions

  So whichever ratio was to be recognized between the range of 27% or 30% – or some rationalized you-tell-me value – is the question, but let's say:

  > We in fact settled on an amplification ratio of 30%, which indicates a "true" lateral deflection **Reality Factor** of 1.3 going against an unsullied **Normalized Factor** of 1.0; here we emphasize the word "true" just to make a point that we needed be realistic

  Although not authenticated from other nonlinear studies on the same subject (if done by others,) but could we make a blanket statement suggesting or giving an affirmative answer to these questions:

  > *Is it "really" that critical or practical to always calculate the non-linear effect for all **CRG** applications?*
  >
  > *Is it adequate enough by merely multiplying a **1.3 reality factor** to the effect due to $P_y * e_x$ so as to cover everything or everything else and all the side-effects inclusively, and make do without having to carry out a full-blown non-linear analysis?*

  By all means we wish what demonstrated was adequate for simplicity's sake; but before answering the above questions, consider another one:

  > For all causes and whatnot, on behalf of simply supported (versus fix ended) girders, wouldn't our intuition have already puzzled ourselves all along, that for magnifying an initial offset from $P_y * e_x$ by 30% – which by giving the benefit of the doubt – might it be too much, too little or a reasonable "**minimum**" number yet?

  Recalling back in **Chapter 4** under the section "**Crane Runway Alignment and Crane Ride**" that any **CRG** configured as "just-so-inherited" or "just-so-happened" in the real world could dictate the analytical results to a surprising but unique "degree of importance"

  There is no need to drag on the subject unnecessarily any further,

  > Just review the evidence given from the "**c**" values of 0.0214, 0.0127 and 0.0009358, respectively appeared in **Example 6.1, 6.2** and **6.3**; we can conclude fairly that,
  >
  > > No one can guess or predict accurately how a specific girder is to (1) whether meet its fate or (2) perform superbly well in service without running the numbers to back up the claim, although situation may vastly depend on the mix of parameters such as EC_w and βL – and of course the **torsional** boundary conditions also

But let's "assume" that the parameter "c" is out of the picture for a moment and then, shall we trust the "30% magnification" or the so-called "1.3 **reality factor**" whole-heartedly for all simply supported members under torsion's influence?

<u>The answer is "No"</u> or at least not yet

And the reason could be deduced from the following cases in point as we could reuse some of the parameters as brought to light in **Example 6.1** with $\mathbf{P_y}$ = 10 ^{kips} and $\mathbf{P_x}$ * $\mathbf{e_y}$ = 0 except that the value of **c** = 0.0214 has now "**fictitiously**" doubled to **c** = 0.0428

Just don't forget $c = [\beta L / 2 - \tanh(\beta L / 2)] * (d / 2 + d_r) / (2 E C_w \beta^3)$, so obviously it takes a lot to double its value. Herein as a friendly reminder to all Readers, there is no way to continue the study any further if we insist on using **Flexure Analogy**

<u>Special Case 1:</u>

$\mathbf{e_{x0}}$ = 0.5

$\delta_{x1} = 0.0428 * [P_y * (e_0 + \delta_{x1}) + P_x * e_y]$
$= 0.0428 * [10 * (0.5 + 0) + 0] \quad = 0.214$

$\delta_{x2} = 0.0428 * [10 * (0.5 + 0.214)] \quad = 0.3056$
$\delta_{x3} = 0.0428 * [10 * (0.5 + 0.3056)] \quad = 0.3448$
…
$\delta_{x10} = 0.0428 * [10 * (0.5 + 0.3739)] = 0.3740$
$\delta_{x11} = 0.0428 * [10 * (0.5 + 0.3740)] = 0.3741$
$\delta_{x12} = 0.0428 * [10 * (0.5 + 0.3741)] = 0.3741$
$\approx \delta_{x11}$

Reality Factor = (0.5 + 0. 3741) / 0.5
= 1.748

Suddenly it takes **n** = 12 cycles to converge and the resulting factor now is almost 1.75 (instead of 1.27)

<u>Special Case 2:</u>

What if $\mathbf{e_{x0}}$ = 2.0?

$\delta_{x1} = 0.0428 * [P_y * (e_0 + \delta_{x1}) + P_x * e_y]$
$= 0.0428 * [10 * (2 + 0) + 0] \quad = 0.856$

$\delta_{x2} = 0.0428 * [10 * (2 + 0.856)] \quad = 1.2224$
$\delta_{x3} = 0.0428 * [10 * (2 + 1.2224)] \quad = 1.3792$
…
$\delta_{x10} = 0.0428 * [10 * (2 + 1.4958)] = 1.4962$
$\delta_{x11} = 0.0428 * [10 * (2 + 1.4962)] = 1.4964$
$\delta_{x12} = 0.0428 * [10 * (2 + 1.4964)] = 1.4964$
$\approx \delta_{x11}$

Reality **Factor** = (2 + 1.4964) / 2
= 1.**748**

The factor/ratio remains at about 1.75 even after we increased substantially from $\mathbf{e_{x0}}$ = 0.5 to $\mathbf{e_{x0}}$ = 2.0

What does that tell us?

*The last two special cases had clearly demonstrated an important fact: the **Reality Factor** would increase as "**c**" value increases.*

But that is not enough to fully satisfy our curiosity yet, let us "**fictitiously**" double the **c** value once more to **c** = 0.0856 and see what happens:

Special Case 3:

$\mathbf{e_{x0}}$ = 0.5

δ_{x1} = 0.0856* [P_y * (e_0 + δ_{x1}) + P_x * e_y]
= 0.0856* [10 * (0.5 + 0) + 0] = 0.428

δ_{x2} = 0.0856* [10 * (0.5 + 0.428)] = 0.7944
δ_{x3} = 0.0856* [10 * (0.5 + 0.7944)] = 1.10798
…
δ_{x10} = 0.0856 * [10 * (0.5 + 1.4958)] = 1.4962
δ_{x11} = 0.0856 * [10 * (0.5 + 1.4962)] = 1.4964
δ_{x12} = 0.0856 * [10 * (0.5 + 1.4964)] = 1.4964
…
δ_{x60} = 0.0856 * [10 * (0.5 + 2.97191)] = 2.97196
δ_{x61} = 0.0856 * [10 * (0.5 + 2.97196)] = 2.9720
δ_{x62} = 0.0856 * [10 * (0.5 + 2.9720)] = 2.9720
$\approx \delta_{x61}$

Reality Factor = (0.5 + 2.97196) / 0.5
= 6.94

After **n** = 61 ~ 62 cycles of iteration, obviously there is no need of going any further since the pursuit of **reality factor** becomes "**unrealistic**" and that has become rather academic at this point. A **reality factor** of 6.94 would be unbearably too high for any girder to survive a **c** value of 0.0856. The morale:

*The greater the **c** the worst it would get*

It should be very interesting to "see" what may have controlled the "**c**" value in general, and from **Example 6.1** for a simply supported symmetrical girder subjected to a concentrated torsion at mid-span it could be expressed as:

$$c = (d_{SC} + d_r) * [\beta L / 2 - \tanh(\beta L / 2)] / (2 E C_w \beta^3)]$$

With **E** being a constant, the controlling factors (or variables) are visibly:

$\mathbf{d_{SC}}$, $\boldsymbol{\beta}$, $\mathbf{C_w}$ and $\boldsymbol{\beta}\mathbf{L}$

Most importantly in which $\mathbf{d_{SC}}$ is the vertical **y**-distance measured from the rail base to the **shear center**. What does that tell us is (1) the greater the $\mathbf{d_{SC}}$ and/or the greater the girder length the worst reality factor we will get and (2) if the **shear center** location is incorrect to begin with then the analysis will be all wrong

The morale is don't assume where **shear center** is without that being justified by calculation

- The final tally among all cases on the nonlinear rail float study:

  It takes about six cycles at the most to reach convergence into the final offset value for low end value of **c** and up to 62 cycles for very high **c** – that gives a good indication that as if the "softer" the "noodle" the more cycles it would take to converge − *or would we say to a point mathematically it might never converge in some cases?*

Being serious-minded engineers doing serious engineering work, we know it's all academic up to this moment, but for a certain ***reality factor*** *to go up to as high as 6.94 in the last example, wouldn't someone – engineer and non-engineer − be leery that this is a sure sign of large deflection event taking place and would that lead to* ***torsional instability****?*

- The **final** rail offset value at convergence would probably spur unexpected serviceability issues if not accurately estimated and contained

(c) *The longitudinal stress due to lateral rail offset or so-called misalignment even at modest amount has been proven to be not negligible at all*.

While designing our structural members of any configuration, the assurance from all as established up to this point would be, not only we should pay grave respect to the effects owing to rail offset but also should always strike an optimum balance among inherent section/material properties in every aspect (**E**, **I**, **Q**, $\mathbf{d_{SC}}$, β, $\mathbf{C_w}$ and **βL**, etc.) and be ready to give a fair evaluation of the design result and provide answer to a very simple question such as:

> *Is the* ***Crane Runway Girder*** *too healthy and too strong for flexure yet too flexible and too weak for torsion?*

But specifically, a few finer points should deserve our further attentions or recognitions:

- Here we are repeating the truth once more; rail offset does have its place to stay in all **CRG** design even without ANY lateral load's influence

  Certainly the situation **should only get worse** when combining vertical wheel load and lateral thrust together as visibly shown in **Case 4**, **Example 6.1**. How much rail-offset amount should be allowed realistically for engineering analysis should always be clearly identified in the project design criteria

- Every example given herein on rail offset was based on a "**single wheel applied at the girder mid-span"** that has no wheel load impact factor imparted yet, but the wrecking power from that is already in the showing, especially for those *torsionally flexible girders*

  As for how much more harm could the effect of wheel offset bestow onto any particular ***CRG*** *under more pronounced conditions such as (1) multiple (moving) wheels (2) with vertical impact and (3) with lateral thrust combined, etc. would require careful assessment case by case using rational approach,* otherwise the results (in terms of deflection and/or stress) could be too conservative, or could just be the opposite, or for the worst be plain meaningless

- Last but not least: For unsymmetrical sectioned girders, always make sure the **Shear Center** is correctly located

6.8 Runway Structural Design Information Process – Planning

Consider analyzing **CRGs** for a very simple setting with specification given as follow:

> A single crane with two **equally** loaded wheels under each end truck

It can't be any simpler than as furnished, but the fact is, we should anticipate situations much more complex than that in real life, and how do we deal with it then?

Given the circumstance, things can get fairly complicated by vast inspiration.

> When guided with contrasting ideology on how should our engineering-analytical source information be culminated, organized and integrated into the **design input packet** – meanwhile if deliberating *rail misalignment* and incidental **Input-Output** *and everything in between* on an expanded perspective – thereof foreseeably it might render many versions of adaptation, as each with varying details suiting various ploys in data logistic planning and whatnot

Here we are (1) on an expanded perspective on specific purpose to advance an ideal blueprint for which and (2) with ultimate goal of solving extremely complex **CRG-related** problems in mind, it should become evident once we start the action and realize that, the amount of resource needed in planning an automated engineering process for the case in point could be much more immense than we think depending on (1) how ambitious our goal is, and more importantly (2) which data management tool were to be exploited to accomplish that goal.

At this point, many Readers may speculate further on what expanded perspective is all about.

> This has to go back to re-recognizing the undeniable fact, **CRG** is so unique, not by its geometric configuration but by the ways how it must defend itself against the "harsh load treatment" it acquired during "normal" service
>
> Naturally on our good term, the scope of engineering treatment strategy we owed to **CRG** must be "wide and harsh" enough in order for it to carry on through its anticipated life span
>
> This gives rise to the need of setting an engineering solution goal way beyond observing conventional paradigm limited by simple design loading specification; so once again the extra burden in the planning is upon no one else but us
>
> Once the target goal is firmly set, in turn the win-or-lose of implementation should highly contingent on (1) how knowledgeable we are in what it takes to complete an all-inclusive full-blown engineering treatment especially when carrying it out by manual means, (2) how sophisticated that we are able to craft the *wide-ranging data manipulating scheme* to suit, and (3) how effectively have we exploited a customized scheme of similar nature, which for this case to function in a supporting role to accomplish our engineering objectives, etc.

Collecting engineering-ready facts and figures is basically a top-down process. It should be straightforward if for handling single crane/simple loads on structure having simple geometry, with or without a normalized data handling scheme – although that could be wrong.

The curiosity is; what if the given specification involves a much more complicated setup?

> Take the challenge from a real-life example; just deliberate and appreciate what it might take to round up and organize the design input for a **CRG** to serve under an unusual situation of:
>
> (1) Supporting multiple high-capacity cranes on the same runway,
> (2) There for each crane the end truck were a dozen or so **unequally** loaded wheels,
> (3) Having series of wheels arranged under the end truck at odd spacing in succession,
> (4) Running the (moving) cranes in various schemes into assortment of load cases
> (5) Qualifying the structure per fatigue and non-fatigue design requirements, etc.

Facing such a *surprising yet not surprising challenge*, it pays to just "think way ahead" first. **Serious application** in special interests of **CRG** requires **robust** data management schema to aid in systemizing those mostly unrefined statistics into **CRG-engineering-friendly intelligence**, because the correctness of every piece of information in every mode of subsistence that passes through the processing chain is vital to proper qualification of structural adequacy.

> That means any **serious** data management plan (to be) adopted – established by the book or not − for analyzing any generic **CRG** for any given design specification must be able to sort out information logically and turn out results flawlessly
>
> It also subtly suggests – or warns – that if the plan has not been tried and tested for broad-based real-life/hands-on applications then, the plan would only be as good – or as lousy – as that of superficial mind's eye, especially watch out for those schemes promoting use of flexure analogy or intentionally avoiding torsion and fatigue all together

Importantly, again, unless we had journeyed through the comprehensive series of **CRG Engineering Actions and Adventures** catering to such a demanding crane load specification in full tilt – or perhaps imagine doing it manually for a change of regular routine – one can never fully appreciate the extent of data management drill/skill/effort is needed in fashioning *non-engineering oriented procedures* and in fine-tuning which exclusively for meeting the ***CRG*** *engineering design qualification obligation.*

> It always makes good sense to bring forward a robust data collecting schema that works for all situations, **CRG** or **non-CRG**
>
> When all is said and done, the bottom line for all applications of all interests remains the same, i.e. *only if we can demonstrate that the desktop application result can complement the findings collected from the field*

And thus to that effect, the planning of **CRG Engineering Process** by automation isn't a superficial chore at all. It beckons the amenities of a rather heavy-duty non-engineering based data handling modules/utilities/system to orderly streamline the tedious (information) procedure involving not only the input but also the output and everything in between.

So besides looking after the as accepted basic geometry and loading information, a better-structured data input scheme must accommodate all situations not only as given but also that as required.

Should the literal meanings of "**Engineering Information**" and "**Engineering Data**" be interchangeable at large then from a project management standpoint:

> Dare someone/anyone to ask and (not) give an answer to; would it be more desirable to start fresh off a universal **CRG** scheme geared toward streamlining information/data collection process suiting any and all levels of project complexity?
>
> To prevent from getting out of hand in any data **I/O** sessions or throughout any stages in between, we could/should give it a try of a plan (engineering data management scheme) with business-like mindset mimicking an **IT System Analyst's** approach in steps, on behalf of **CRG** engineering, briefly that might go as follows:
>
> - Identify loading "**I/O**" basics from among all credible crane runway load sources involving **data classification** requirement
> - Pick out what are most significant as for the "**I-input**" part involving mainly **data collection** requirement
> - Figure out how many unique, independent and/or mutually dependent elements that are there for the "**O-output**" part involving mainly **data organization** requirement

- Set up data structure for the **I**s', **O**s' and what's in between and beyond involving mainly **<u>data relationship</u>** requirement

- Work out detailed strategy concerning each must-do activity involving mainly **<u>data manipulation</u>** requirement, and so forth

Pushing the same phrase or word entangling "data here data there" too many times seems like a catchy marketing ploy ongoing, and yes, it does and there is a reason for that.

As matter of fact it is a marketing ploy, but on a better intent and for better outcome; it should take no time to catch on the concept of connecting the atypical **CRG**-unique engineering chores with the all-natural data management chores, there it would form an intuitive association as we shall see.

> Even though the emergence of literal "data" can be seen as somewhat sidetracking away from our *normal* train of thought on **CRG Engineering** interest for the moment, but, in retrospect while handling matters in our *normal* engineering practice or most of other *normal* business applications at large, already, most of us must have disciplined ourselves in some ways or been well trained to manage/organize "engineering data" whenever we "accumulate" facts and figures, "make" calculation or "prepare" to "make" calculation, "make" a numerical tabulation or "present" our calculated results, etc.
>
> Thereby once we try doing things in ways similar to establishing "*data normalization routine*" as if exploiting the attributes furnished in a mainstream commercial-themed venture or adventure, the aspiration is the same whether on engineering or non-engineering purposes

With *data normalization* on practical **CRG** purposes in mind, the task of **Crane Runway Loading Collection** needed be (or should be) broken down into as many "aggregate" chores as needed, then one at a time with components associated with which clearly identified.

At the heart of the action, certain pieces of "information" may appear conflicting to one another if starting out without a well thought-out data hierarchy setting. The confusion could result from an inadvertent oversight or overdone, or on no specific intent: For instance, information sparingly given might seem as if undersupplied, but then some other information might appear excessively provided as if redundant, then what do we do?

Regardless to how we proceed, the key is imagining ourselves in similar capacity as if an **IT System Analyst** being put in charge, then doing it through logical planning, based on data **I/O** requirements (beyond engineering requirements) and drilling down the nitty-gritty, one task (or subtask) at a time. To start the development, it may involve:

- Entity identification (data labeling, indexing and assignment of attributes with enumerated parameters, descriptive texts, keys or keywords, etc.)

- Data structure hierarchy, data relationship dependency, etc.

6.9 Runway Support Loading Input – Specifying

The contents being communicated hereinafter were Authors' opinion for information purposes only. The nonbinding concept being provided as follow may need to be modified or customized further to suit.

If we were to **normalize** the **Crane Runway Loading Information** (data) like a pro does with intention of tackling <u>the most complex or the worst-case scenario</u> then, there are a few tasks that needed be set up in succession so that the data structure schematic is optimized with best interest to deal with most situations.

That said, the true message is,

> Traditional old-school desktop data collection strategies for dealing with vast amount of information often relied on provision of "ample storage" to stockpile discretized entities such as tables, graphics or text files, etc., and that's about it
>
> What lacking is the basic management tools and facilities built on robust data relationship model in order to maintain data structure integrity, which leaves significant inconvenience in how data are tabulated, organized, displayed and manipulated to suit specific application's need
>
> Often times in the old days, the application-specific data organization, to a great extent, is unstructured; in that the mix of discrete entities although were maintained orderly in the same depository neighboring to one another but usually went without explicit relationships defined among them thus making it (extremely) difficult to "enforce" data referential integrity
>
> The matter of concerns as a result, it places heavy toll to the *backend* data administrators and the *frontend* end users; even simple chore such as performing basic data cross-tabulation, sorting and/or maneuvering information in and out of the data domain can be an unpleasant experience
>
> To follow up along with fixing such shortcoming and to make the most of **normalized** data structuring technique, it is anticipated at the minimum, the filing format and organization of unstructured flat-file-styled data record/assembly need to be modified drastically or be completely restructured
>
> The basic procedural framework of **data normalization** is not much fancier than those already "qualified" day-to-day practices based off our professional common sense with fair amount of "rethinking" keen on establishing customized data relationship hierarchy, and that's it
>
>> Through such customized data structure makeover, "supposedly" a seemingly disorganized chunk or collection of data can be **normalized** into a number of logically associated data subsets, in turn into as many prearranged depositories as needed, thus minimizing superfluous specification of redundant information
>>
>> In an elementary setup, entities sharing the same domains were created individualistically but can be linked logically as dictated by the pre-established hierarchy. Yet in application setup employing more advanced linking approach, cluster of domains may reside physically either in one single integrated system/directory or may spread out in multiple systems, locally or remotely for practical reason
>
> All domains were suitably associated – explicitly or implicitly – through as many made-to-order data links as conceived by design needs. Depending on how sophisticated the application is meant for specific project, the duration of existence for data links can be either static (permanently assigned in advance) or dynamic (temporarily created on the fly in the middle of process)

All that being brought up is intended to construct a robust data management system that is easier to maintain on purpose of (1) preserving data integrity and (2) minimizing data redundancy, etc.

As per prescribed scheme:

Task #1 – Generic Crane Identification:

> Think big beyond single crane operation:
>
> Once accepted a multiple-crane specification and ready to take up to the task, the first thing first is assigning crane label

It is more practical to assign unique alphanumeric label to each crane such as **1**, **2**, **A**, **B**, **01**, **02**, etc. to clearly identify each individual crane apart from another – doesn't matter if their mechanical attributes and wheel loading specifications are identical or not – because every crane is a justified load source to the girder

Not big enough:

Some of us tend to go lean too soon and then fall for shortcuts in database setup; that might be **OK** at some point later on based on data-management design review as deemed appropriate or as necessary to weed out (data entry) redundancy, but don't do it at this early stage

On making the point across, if there is only one crane then use one label, if there were two cranes then use two or more labels, as so on, but,

Take a realistic example:

Two cranes had been designated on duty along the same service aisle, both cranes could be identical or dissimilar in the wheel loading specification, for which the operator might (1) run one single crane at a time or (2) run both cranes jointed in series

Getting set for data management:

For identification (**ID**) purpose, one needs to assign labels such as **A** and **B** for the two cranes, and that merely takes care of the **physical** count; but **logically** there is need of additional label, say **C**, which represents the case joining both **A** and **B** in series

Therefore in a general setup,

Accounting for two cranes in series may require three labels designating that "three" is the maximum count by reasoning; so there could (and should) be three separate load (or load combination) cases whereas (in rare occasion) three cranes may require a maximum of five or six labels, and so forth, but so doing only as required

In a much more elaborate setting,

Although what normally given rarely exceeds two cranes but still that has a logical or mathematical potential to come true

The rationale of counting all probable load cases for multiple crane applications could be deduced by playing a common-sensed **ID** combination and permutation game. Do whatever is needed to, but only if multi-crane operation is truly applicable and truly logical from an Operation's point of view, otherwise the extra effort may just be wasting of resource (a huge database burden)

Continuing with Task #1 on remaining crane-specific attributes:

Associated with each crane, there is a range of information – give and take – for **various intents**. To **CRG** engineering with specific crane in focus, make sure every significant attribute that could be mutually and uniquely "**related**" are appended after the crane label

As per governing design criteria, a number of specific elements of information typical of structural engineering interest may include but not be limited to these:

- Type of crane: Mill crane, ladle crane, etc., which may dictate what specific load factor is to be associated with what specific load combinations and
- Percentage (apportion) of **Total Lateral Thrust** against maximum wheel load to be taken by the **CRG**, and so on

From a Data Design rather than Engineering viewpoint:

Visibly, some of those attributes may be established as either optional or mandatory field entries, depending on how important they were and how their subsidiary data were to be "tied in" or "looked up" through data link(s) or be categorized into the design input data package

Clarification:

During data record entry, when the cursor is landed in a "mandatory field" signaling that a *non-null value* must be provided, only then to be recognized by the system that the user action is complete, otherwise either the cursor exit movement is locked out in place or else the status of the record is left as unfinished until a valid entry is supplied to the "mandatory field"

Task #2 – Crane Wheel Loads:

Applicable to each labeled crane:

Arrange for all participating wheels in proper labeling order then assemble load information for each active wheel that may include these sample fields:

- Active crane label
- Active wheel sequence **ID**
- Vertical wheel load magnitude
- Distance measured from the active wheel to the preceding (or trailing) wheel and
- Whether if it is a drive-wheel, etc.

What as itemized were some (if not all) of the essential fields being included into one data record applicable to one specific wheel

> In other words, for each active crane of matching label, the data entry in like format/pattern should be repeated for as many records as required for all vertical wheel loads whether of equal or unequal magnitude

In the end, each data record should correlate with a unique combination of crane label and wheel (load) sequential **ID**

> *In carrying on with the same example cranes, say, if physical crane **A** has two wheels and physical crane **B** has four wheels then the logical crane **C** should have a count of six wheels. When all was said and done, we ended up with a wheel load data table having total number of* $2_A + 4_B + 6_C = 12$ *records*

Evidently one could disperse with more or less information imparted as seen fit for task #2, but from such a basic listing it should be sufficient for (1) starting the influence line analysis and (2) enveloping the structural responses

Task #3 – Load Combination Identification:

For each load combination case, listing for which the:

- Load combination case **ID**
- Active crane label
- Flag whether if fatigue check is applicable to the load combination

- Load factor for vertical load considering condition either with or without impact, and specify if the load combination is for either single crane or multiple crane application

- Load factor for lateral load considering conditions with or without reduction for fatigue evaluation, and

- Load factor for traction load application, etc.

<u>Data quality of crane load specification</u>:

Some of us may need to fashion a data structure scheme deemed (1) as comprehensive, (2) as being practical and (3) as complete as with all-inclusive supporting statistics – could be numerical or text information – and so on. But the best testimony to establishing a robust data scheme should come from one of:

- Those that allow for all users of all project objectives to gather and preserve the entire packet of **Crane-Specific Information** (**CSI**) in one take, and with that,

- Those being able to **correlate seamlessly** with other elements of associated design input data brought on already from Tasks #2 and #3

Otherwise the data being collected could still be deficient, incomplete or contain erroneous, redundant or confusing statistics, etc.

<u>Task #4:</u>

Ideally − but only **as needed**

> The all-inclusive **Crane-Specific Information** (**CSI)** should be incorporated into a separate task of its own; and thus there might be a need of creating a <u>Task #4</u> as suggested herewith

This could be established for each given crane including key **CSI** input items such as *lifted capacity, trolley weight, trolley wheel spacing, bridge weight and bridge span*, etc. that are beneficial and/or necessary for <u>double-checking</u> – by us or our peer viewers or by programming means – the maximum total vertical load sum applicable at either end of the crane aisle

On occasions, instead of making all **CSI** input items mandatory, it might work better by leaving some of that as optional, because not all the **Rehab or Replacement/Upgrade Projects** (**RUP**) info − supposedly useful in general terms − were necessary or suitable for structural engineering purposes

Sometimes maintaining "optional info" as "optional" is the thing to do. Of positive sense, it creates a data depository or place holder that not only allows both input data Preparer and Reviewer to settle on a common design wheel load basis – kept for record or for reference − but also more importantly made it clearer for future Engineering use *should one day the current **RUP** become another forthcoming **RUP** down the road*

Other than as mentioned, what should really be mandatory (not optional) in <u>Task #4</u> are the crane-specific load magnitudes:

- The vertical load $\mathbf{P_y}$
- The lateral load $\mathbf{P_x}$ and
- The traction load $\mathbf{P_z}$

To avoid any inadvertent misunderstanding owing to "double billing," a more advantageous technique for handling numerical data in the **X/Z** load input detail involving all **3-D** space is through numerical normalization using relative ratios with respect to load $\mathbf{P_y}$;

> Thus more often than not, $\mathbf{P_y} = 1$, $\mathbf{P_x}$ and $\mathbf{P_z}$ are in fraction
>
> This approach is more clean-cut than by other customs, herewith without having to deal with actual load magnitude since the true denomination for each wheel can be derived from a value that had been taken care of in Task #2 already

---

Numerical normalization technique could come in handy beyond specifying crane wheel loads, especially with some of those notable environmental loads pertinent to selected **CRG** structures in addition to resisting mechanical (crane wheel) loads.

> To loads of certain characteristics, for which applying normalization suitably may free us from being burdened by creating additional Tasks

As follow is an example of how environmental loads can be included as part of the input:

> For certain Mill Sites (1) susceptible to earthquakes and/or (2) having portion(s) of the plant facility whereby the crane runway extends into an outdoor area/zoning with unusual terrain exposures such as situating at much higher elevation over the adjacent topography, for example, more than 100 ft above a reference datum, etc., the environmental effects from **inertia loads** due to earthquakes and **surface pressure** from winds could become substantial and that needed be evaluated for record purpose, etc.
>
> In reaction to what given, the up-to-the-minute objective is to figure out, can the existing setup take in a combination of (1) *point (wheel) load,* (2) *surface (wind) load and* (3) *inertia (earthquake) load* onto the same girder; and how to deal with the situation, if possible, without making drastic change to the existing scheme
>
> To credibly instigate environmental loads into the entrenched **CRG** design input packet without messing up the mechanical (wheel) load input could be as easy as 1-2-3 as we think it would be on the whole. But the actual commission in setting up a *relational data structure* aimed at unifying a variety of loads of dissimilar natures – notably each of respective dimensional unit − without a major overhaul of what's already been settled beforehand could be a bit tricky to lay our hands on
>
> In essence, the need is a generic plan to cover loads of all different nature the best we can, and that in particular to effectively handle the environmental loads; there is a fat chance that it might lead to furthering the complication in development or extension of a relational data scheme already worked out; and thus how not to bring on excessive data design/handling overhead warrants a careful thought over

When went by **non-CRG-oriented** structural loading data input convention, ordinarily each one of these "environmental" loads or effects were treated as independent **I/O** event; what being facilitated for each event was an independent data entry slot, "usually" isolated from the mechanical (wheel) load input batch − which follows a special data entry instruction based on different algorism

But on relational data design's and **CRG's** behalf, shall we do something similar or not at all?

Yes and no, depending on (1) how well we interpreted or misinterpreted the characteristics of the loads and (2) how well we incorporated their equivalence into the existing input stream

One needed be careful of what we were doing, that's all. It may turn out well for intended purpose without being critical about the not-100-percent-perfect outcome; yet it may not work out in some cases for practical reason yet to be exploited

Nevertheless, prior to implementing the as-mentioned environmental load input, how to effectively "**merge**" the effects from the inertia earthquake load and the surface wind pressure – of dissimilar numerical dimension units – with the load effect from concentrated moving load without creating separate input task(s) is what we are seriously after

As always, the "upper bound" of these environmental effects could be calculated ahead of time per relevant Code Intent or Design Specification/Criteria

With exercise, these effects can be summarized or transformed into realistic design forces and/or moments (resultants) with respect to girder's **shear center** or the **elastic centroid** whichever deemed appropriate

The idea at this point is coming up with something <u>not 100-percent exact</u> but <u>close enough</u> that being <u>equivalent</u>

So long as the "assumptions being applied" were "technically qualified" and the "resulted approximations" were numerically reasonable, then however/whatever that is, is immaterial herein as to how accurately it was done

Before moving further, just so we make sure that in certain practices, the effects from <u>earthquake load applicable to the girder including the weight of the crane</u> and the <u>operational crane live loads due to lifted capacity</u> were not combined in the same load case for good reasons

The key is focusing on the realistic upper bound effects. *Once that was completed then one can move on to establishing data compatibility among applicable load effects*

As closing step, these forces and moments resulting from surface load and inertia load could always be resolved and proportioned (or normalized) further using whichever approach deemed appropriate into:

- Either as <u>equivalent</u> uniform load like Dead Load but pointing into **Z** direction or as Live Load into **X** direction as add-on through proper factor(s)

- Or as <u>equivalent</u> concentrated $\mathbf{P_x}$ and/or $\mathbf{P_z}$ in ratios or percentages/load factors with respect to the true wheel $\mathbf{P_y}$

What depicted seemed <u>as if</u> playing trickster to existing system yet executed with minimum added data management overhead. And finally all could be consolidated into one or more new load case(s) <u>as if</u> they are some other forms of mechanical load as supplemental to the regular crane load input

Comparing the outcome using <u>equivalent load</u> method with the "real thing," in some way what established into a part of our design criteria could be artistically double-dealing but of good-natured meaning that it's more than a reasonable tradeoff for technical expediency

<u>Good to be a bit hesitant first</u>:

Don’t hurry up into the numerical tackling mode just yet; everything intended herein is approximation and only good for what if it’s good enough without doing the real thing. Readers who had any doubt/disagreement on the approach could find out by themselves how “costly” or how “difficult” it is to do the real thing

Hidden caveat and difficulty:

Once decided it’s the way to go, but before actually punching the numbers, already we must have a pretty good idea of the girder’s geometric configuration, which shouldn’t be a problem if we were in on forensic investigating or qualifying the adequacy of an existing girder, because “everything” is (supposedly) known and given – by proper calculation

The significance: Ahead of using equivalent load method, one must have a firm grip of the girder’s depth, dead weight (mass,) the location of the **elastic centroid** and the **shear center** among other attribute, otherwise it could lead into a garbage-in-garbage-out situation **especially** if the girder had an **unsymmetrical profile**

After following through with the load data organizing tasks as delineated thus far, some of those more observant Readers may have already been taken in so seriously, and be ready to deal with the mess in steps, or otherwise entirely turned off from the whole idea.

Yet unmistakably as demonstrated, the resulting crane load data collection scheme being spewed out in tidbits here and there – through a modular approach – might have etched an impression that on outward appearance, the “look” of tabulated data tables are still very much flat file-like or spreadsheet-like, isn’t it?

It could be more wrong and less right only if judging things by the look, as matter of fact they were **not spreadsheets** but instead everything in sight is very serious **relational database-like in nature** as a whole.

Without further hesitation, all as illustrated is a **relational database** setup for real:

Notice that “**Crane ID Label**” is the most significant piece of information out of the entire setup. Viewing from a relational database design position, it is actually a **primary key** that stands out as a unique data record identifier

“**Crane ID Label**” in so defined as far as a database table is concerned, every record is unique in its own way, i.e., no two records within the same table can be assigned with the same key value, even if we try to do it purposely

Suddenly yet subtly, an important fact to take in;

The data organizing approach being advanced in specifying Runway Support Loading Input as demonstrated did indicate that it was achieved through a serious business-like undertaking, which is not just a catchy marketing ploy in substance

After all, using spreadsheet, database or any other ways and means for organizing “Runway Support Loading Input” to attain the same goal (or not) is a personal choice

For solving the same problem, as always, there are numerous approaches to analyze and dissect the raw statistics, and subsequently to allocate from information supply-and-demand relationship into as many sets of flat file table, spreadsheet, database table or structured text file as there could have been

So once the decision of solving engineering problem with a touch of database insight has been made then, the input data structure should be carefully planned out and finalized

As for provision of practical **CRG** loading data input application,

> No matter what scheme as driven from *different* mindsets from *different* individuals on *different* causes, the overall throughput yielded from any given set of data structure from any individual design could only be critiqued subjectively into two categories, either the *efficient kind* or the *inefficient kind*

In author's opinion on **CRG** loading specification, there is hardly a clear-cut distinction between a right/perfect data structure and a wrong/flawed data structure

As a database primer as for tending the chore on hand:

It is imperative to understand (obtained from other resources) the definition and the proper usage of *primary key, secondary key, lookup key and composite key*, etc.

Kind of database-specific small talk:

To go further than establishing primary key, we should stave off all potential "key redundancies" by merging the definitions under multiple tasks into a single database "record" meaning that to be combined into an ordered set of values as necessary

After all, the "Crane Label," being the **primary key** under task #1, would become a **foreign key** under task #2 and be a part of the **combined key** (or **composite key**, **compound key** or **superkey**) under task #3 in conjunction with the load combination case **ID**

6.10 Rail Offset – The Referential Issue

Back at the beginning of this **Chapter**, therein the "static moment arm" along **X**-direction – which led into torsion once paired up with $\mathbf{P_y}$ (the vertical wheel load) − was referred to the "phrase" such as *rail offset, rail float or rail slip, or be generalized as rail misalignment*, etc.

Even though for practical purposes, an individual's perception of one phrase against another could be similar or arguably different from trade to trade as if there is an identity issue;

> Yet numerically speaking, to us as far as the Structural Engineering Attentions are concerned, all of that would be recognized herein as a consequence of **geometric and/or loading imperfection**

By that virtue we would stick with the universal namesake **Rail Offset** before further discussion or making any calculation *unless noted otherwise*

Regardless to whichever **Rail Offset** value was assigned (measured) for engineering evaluation, but in all fairness, based on what exhibited in prior calculation (see **Examples 6.1 through 6.3**) we find it impractical to argue with the fact:

That "the true state of structural suffering" or "the true extent of structural response" resulting from the prescribed geometry/loading imperfection always ends up being much more severe than what it was intuitively "triggered" − owing to amplification associated with the incremental nonlinear effects − and thus by an adapted conscience:

We should think twice before accepting any given rail offset condition by its face value

Speaking of geometric imperfection − be it of transient or permanent in nature − once exposed in the open, with or without influence from additional loading, could only get worse (during **CRG's** ensuing life span) and what's already there would never magically disappear on its own if it were not carefully evaluated, rectified, mitigated or kept under control.

Whether by design mandate or by personal conscience on accepting such inconcealable imperfection as an authentic "design condition", one wonders:

What is the reasonable value of rail float to be adopted for practical CRG design use?

A rather straightforward question as it appears; but before a reasonable answer can be given on this subject, it calls for a delicate and fairy lengthy account of some of the <u>facts</u>:

> By "literal" suggestion, "rail misalignment" sounded more like the consequence coming from an actual observation (by visual means or by survey equipment,) or rightfully so concluded as the straight measure of a <u>fixed amount</u> of static displacement
>
> <u>Simply put</u>:
>
> Misalignment is the gauge of "how much" the crane rail has deviated from the "norm"
>
> > Therefore, regardless to the accuracy of "how much" as given, from a quality assurance standpoint on engineering-inspection and/or surveying contractual reason, the numerical value being <u>fixed upon</u> should not change at all once the "value" had been officially reported, or else there would be no end to it for argument's sake
> >
> > *But to us in the number crunching business, one way or the other, the measured result in black and white is either zero or non-zero*
> >
> > Thereby to Engineers, the basic understanding of "misalignment" seemed to favor an awareness that once what was there as fixed, it should stay being <u>static</u> as is
>
> But on the other hand, it draws a completely different impression from reading out loud the term "rail float" or "rail slip"; by which it insinuated as if something briskly <u>dynamic</u> in characteristic had "happened" owing to the vividly prompted verbiage: *float* and *slip*
>
> > For the duration of an <u>active</u> loading-unloading session being driven at Crane Operator's control, in response to combination of Trolley, Lifted Load and Crane Bridge's **X**-bound movements, the rail could deflect <u>passively</u> back and forth along the **X**-axis accordingly, but only to meander locally between rail clips
> >
> > By enumerating the rail movement as measure of how the crane rail may feel (or suffer) during the act, both "float" and "slip" may be looked on as a display of some degree of <u>lateral rail deflection</u>
> >
> > In actual calculation, the range of "float" or "slip" needs be represented in <u>vector sense</u>, and if the value of which were to be treated as standalone design load case (or load cases) then it should bear either a positive or negative sign with respect to the "norm" beyond usage of an absolute value

Terms such as deflection, misalignment or offset, whether of numerical, literal, static, dynamic, variable or fixed in nature, must have a "norm" or "reference" against which the measurements were based off. The question becomes:

> ***What does it mean by "norm" and with regard to which entity?***

Here are some general concerns that one may be wondering "what is it" in real life meanwhile regarding the "norm" as if an official inhabitant within the confine of girder's cross section instead of focusing on the rail that sits over the girder flange, then

- How is a **norm** becoming the norm?
- What benchmark is the **float** or **offset** measured against?
- Should **norm** be the **girder web centerline**?
- Should **norm** be passing through the **elastic centroid**?
- Should **norm** be passing through the **shear center**?

Visibly to any one of these questions or to all of them for argument's sake, there might not be a universal right answer or wrong answer. As to any specific application, the consensus on how appropriate an answer that is would depend on what **our spontaneous reference** is.

On digging much deeper into the subject, it might bring out further interests from those as listed into a subset of additional questions, and before long, all of them are in need of separate answers.

6.11 Rail Offset – The Uncertainty

By way of **Examples 6.1 through 6.3**, we capture the "simple" fact that whenever under active crane load's unceasing influence, the absolute value of Rail Offset can always "grow" from its **initial** value – whether zero or non-zero – to reach a **final** but limited amount, there is no need of further examination.

Although "treating Rail Offset as a serious matter" does make qualitative sense, but there seemed no "official guideline" on how to quantify a parameter <u>for practical application</u> connecting the two "**initial** and **final**" values in terms of what exactly is the net growth.

And yet, without seeing a firmed-up quantity certified for practical engineering application, one cannot take the "simple" suggestion from a "simple" blanket statement or some loosely contrived design guideline and then run with it into performing formal stress analysis.

In order to define the value of rail offset for generic engineering design purpose we must get much deeper into the bottom of it. As matter of face, the true exactness of rail offset is never that easy to get our hands on for practical use in the design of **CRG**.

The reason is simple, once again:

> As the girder deflects sideway under **P-δ** torsion influence, the "value of offset" isn't fixed at first, but instead has to go through a **transitional** stage as that made obvious in **Example 6.1**
>
> Anyhow, it would not be a fixed value unless the "offset" was confirmed from a known **steady-state** source, otherwise there is no way of predicting it <u>accurately</u> ahead of the not-yet-started calculation, making it a perfect example of catch-22 condition
>
> What it takes to grinding through the process similar to that as demonstrated in **Example 6.1**on behalf of an **I**-shaped beam is good enough for us to appreciate how tedious that has been, let alone the application involving <u>unsymmetrical sectioned members</u> – which, we shouldn't forget, is the main focus of all the **Chapters** – but, how accurate or inaccurate could the rail offset be measured becomes our next focus

So far so as understood, what circumscribed as much about the intricacy in narrowing down a suitable amount of rail offset for practical purpose isn't that easily achievable. It certainly brings to light on questing for a universal value once and for all so it is no longer a shadowy design condition any more.

And to deal with the somewhat reluctant catch-22 situation, a rudimentary way to measure the effect as it transpires was given in **Example 6.1** for reference purpose only; for the least and at best that may only apply to studying "new" preliminarily sized **I**-shaped members under design stage, in particular to those having *not-yet-fully-optimized* profile geometry

But what about taking measurement of an "existing" girder already exhibited permanent offset at the mid-span?

Let us find out whether if the Surveyors could articulate a practicable <u>baseline</u> with goal of delineating rail offset <u>accurately</u> for practical structural engineering consumption by following along these rationales:

- Whether the proceeding of field development is on target or on schedule or not, but as most components are freshly installed, the crane rail is anticipated to center about the **girder web centerline**, which, <u>logically</u>, would be an ideal choice to be the "norm" simply because the web is tightly nudged against the rail base from underneath

  On behalf of $\mathbf{P}_y$, such arrangement should have been all so perfect in facilitating a direct in-line wheel load orientation that can be aligned *from crane wheel through the rail then into the web* for ideal load transferring purpose, correct?

  Yet in order to keep the condition ideal isn't an easy task; we can find out why in no time, there is practically "no easy way" to "preserve the original girder's **3-D** geometry" as-is once fabricated, shipped and installed. That was only a minor issue; what concerns us more is the imminent "disfiguring" in general following prolonged periods of service

  Predictably after "living" through a number of loading-unloading cycles in active duty, how a girder performs satisfactorily or not can only be gauged in contrast to a practical norm however-whichever that was chosen. Why?

  A trip to the Mill is the simplest way to figure out the reason why, because globally the girder may have been so (permanently) crooked, sagged, settled, bent out of shape, displaced or warped, etc. thus any of that can induce referential error owing to the presence of shift, offset, or dislocation between the *rail centerline* and the *girder web centerline*

- As an alternative to girder web, a straight line connecting an on-site work point (not the design work point) based on support column centerline or flange could be the norm next in line but only if that's proven reliable, theoretically

  Think that's more reliable? Not so yet, but why? Again, see it to believe it, a trip to the Mill is a simple way to explain the reason why

  > There were numerous cases in that the tieback supporting column(s) and/or the flange(s) thereof were (permanently) bent out of plumb or out of plane, cracked out of shape or even sheared off completely, thanks to the relentless assault of fatigue stress fluctuation/reversal, or even due to bad tieback element or its interface connection design, etc. – sort of dealing with *misalignment among multiple elements in **3D***

- Then ideally for calculating torsional effect, theoretically, **shear center** should have been chosen as norm, against which all "floats or offsets" should be measured as it should; but again there is a problem, other than dealing with doubly symmetrical sectioned members, the scheme is impractical (Readers are smart enough to know why)

  <u>Reason:</u>

Take a generalized member cross section whether of singly-symmetric or of unsymmetrical shape, for which most Engineers by now should be able to figure out "with relative ease" the **shear center coordinates** on the Office desktop on screens or pieces of paper

Engineers can do that effortlessly, but certainly Surveyors would have no comfortable way locating that same **shear center coordinates** during an on-site surveying session, it is like pin-pointing an "imaginary dot" in the space especially for members of unsymmetrical section, forget that

Not surprisingly, all rationales would lead to a cynical conclusion on prompts per *in-service* field observation rather than *in-office* perfection we fictitiously sought after. After all, we are dealing with misalignment against an indeterminate norm. Then how could we get over the dilemma from sticking so much with **shear center?**

Refocusing from a different position:

We can always assume (assign) the moment arm along the **X**-axis for vertical load of interest = **e** with respect to **shear center**.

If at all possible **e** = 0 then, it requires that everything has to be **perfect**.

Perfect, for example, as in the case for symmetrical sectioned girders when the crane maintains its parallelism on the crane rail, and by which both the crane and the rail are free from ill effects due to over- or under-gauge with respect to the sacred girder web centerline

However, preaching for perfection works more often in theory in Offices than during actual Mill Operations

As pointed out many times over, in the world where **CRG** lives in, nothing is ever perfect. Nevertheless in making structural engineering sense, "loading position imperfection" is no longer measured against the girder web but has to be with respect to **shear center**, thus it is worthy of cutting into the torsion-specifics from a different entry point − the engineering kind rather than the surveying kind

In order to attain the rank of perfection (**e** = 0) that some of us had contrived for, it would take a seamless collaboration of two isolated but closely related factions, e.g. the loading as trigger *in action* to start off and then hopefully no change in geometry *in response*

But is that possible? In the end we should realize the rank of perfection is nothing but an engineering travesty

More expressively on what happens:

- The loading faction in **CRG's** context is the **active** force entity being applied at a given load point within the girder span. Loads that come in a random cluster might be resolved and be identified through individual **XYZ** components, or so the resultant of loads could be resolved into a vector entity

  The attention is not the **XYZ** components at the load point but in the much generalized single-sourced resultant force pointing seemingly into an arbitrary orientation or a **SRSS** randomized vector that follows along a specific and unique orientation

- The geometry faction, as a **passively** generated entity, is the measure from **shear center** aiming into the normal (or along the perpendicular direction) to the said arbitrary orientation which is entirely dictated by the **SRSS**-sourced vector. Specifically, this becomes the true dimension "**e**" for certain that not necessarily points along the **X**- or **Y**- axis in a more generalized rendition

It may be possible out of wishful thinking, if all is well and done perfectly then naturally **e** = 0. But again, the chance of **e** = 0 is extremely slim or none at all

Here is the reason why (bet we all know):

In a harsh and dynamic service environment, each participating entity of engineering interest, whether of *loading* kind or of *geometry* kind, is out of engineering control but prone to suffer inevitable consequences, typically from nemesis of many irrepressible twists and turns into interacting with one another (i.e. $\mathbf{P_x}$ and $\mathbf{P_y}$,) cultivating a much higher degree of difficulty in keeping up with the tip-top status of **e** = 0

Then, again, **e** = 0 is valid only in a perfect loading-geometric setting, *which is an extremely rare condition that takes place only when the **SRSS** randomized vector (if luckily) passes through the **shear center***

So how slim a chance that is, only by guessing if it does

<u>The result proven once more</u>:

Nothing is ever perfect and we seem going around circles.

But enough said about the same writing already etched on our design menus, cheat sheets and check lists; the subject of concern here is how better can we incorporate the imperfection into our design rationally without being too conservative or unconservative, especially after the inspiration as propelled from **Examples 6.1** through **6.3**

There is little doubt that such practical design paradigm should be established with extra care and with viable logic to base on, too. How to achieve the goal in this regard without liberating the <u>geometric</u> constraint too much or shortchanging the original design <u>loading</u> intent, and be technically convincing certainly deserves a lot more deliberation than pure postulation.

6.12 Rail Offset – Design Consideration

What controls rail offset?

Two things, the **girder geometry** and the **applied loads**

To begin <u>on the geometry side</u>:

Unless adopted otherwise for unusual reasons, typically the "crane rail gauge setting" intended for servicing the loading/unloading bay is centered on the girder web − the unanimously elected norm, even if the section profile is unsymmetrical

Therefore if we place emphasis on the reliability of geometric reference to be adopted for purpose of measuring rail offset then, the girder web centerline would be a natural starting **point** – or a starting **line** or portion of a starting **plane**, etc. – for the cause

However, to be practical with an intention to maintain the quality of measured/surveyed result, it would only work out provided that the member (our **CRG**) is *absolutely leveled, straight and plumb from end to end*, in a way everything has to be perfect

It is nearly impossible to maintain everything to be "flawless" at all times in a busy running Mill. That is a fact easily understood for nothing is perfect in a dynamic **CRG** world. As "flaw or imperfection" could creep in from natural deterioration over time, but, on day one, the girder should come into existence free from any "**excessive girder sweep**" to begin with

The important question is how excessive is too excessive

"Girder sweep" is one of the most primitive states of geometric imperfection, which is normally evaluated at the mid-span of a prismatic structural member. It measures the extent of lateral offset of girder's longitudinal centerline bowing away from the norm

In many real life situations, minor amount of girder sweep (imperfection) is almost always unavoidable from most fabrication (once considering the effect of **L / d** ratio that comes into play)

"Sweep," being measured along the lateral **X**-dimension, is simply the deviation of the longitudinal axis from straightness. In the real **CRG** world, a certain amount of offset always exists even if the crane rail is perfectly straight or even if the installation of the rail and those other closely associated parts of the structure were dimensionally flawless or within prescribed construction tolerances, etc.

The important question is, again, what is the qualitative definition of flaw

The maximum allowable girder sweep for design consideration varies from Code to Code and from Guide to Guide. For examples <u>as of this writing</u>:

AISC mill tolerance (as of this writing unless updated to different amounts) sets a limit of 0.125" per 10 ft length

$$\mathbf{e} = \mathbf{Sweep}_{\_AISC}$$
$$= 0.0125\text{"/ ft}$$
$$= \mathbf{L} / 960 \qquad \text{or } 0.001042 * \mathbf{L}$$

While **AIST** pertains a more stringent ratio of 0.25" per 50 ft length

$$\mathbf{e} = \mathbf{Sweep}_{\_AIST}$$
$$= 0.005\text{"/ft}$$
$$= \mathbf{L} / 2400 \qquad \text{or } 0.0004167 * \mathbf{L}$$

It is of no point in here venturing into the sacred reason why or how a certain "sweep limit" was set by a certain Code or Design Guide but to respect that:

1) By setting limits on the "sweep" or "allowable flaw" as design-fabrication-installation standard for all parties involved to observe and

2) By following through with that in engineering practice to show all the good intention on our part

But – with no intent to change the subject – on behalf of **CRGs**, here are a number of sidetracked concerns that needed be clarified:

- *Which guideline controls what we, Engineers, do in general?*
- *Are these guidelines enforceable in the job site in reality?*
- *What if the "flaw" was found exceeded the allowable right after construction?*
- *What to do once the "flaw" was found exceeded the allowable after years in service?*
- *And how does all that apply to unsymmetrical sectioned members?*

If so or for whatsoever – assuming we know what the true amount of allowable flaw is –

> Knowing that rail offset causes torsion, so in other words, as long as lateral load $\mathbf{F_x}$ does not exist and for all symmetrical sections girders, there won't be any torsion if there is no rail offset or as long as the amount of rail offset was kept within the flaw limit then, presumably,
>
> > For **non-CRG** structures that do not suffer from the variety of violence as **CRG** experiences during normal service, thus during the initial structural analysis, it should free us the Engineers from having to "calculate" any nitty-gritty trivial amount of induced stress owing to the "limited amount of flaw" in their calculation when comparing that with other forms of primary stress, sounds reasonable enough.

Now how about the **CRGs**?

> Is all that really true?
> And then, how trivial is trivial?
> What if $\mathbf{F_x}$ came into the picture?
> What about unsymmetrical sectioned members?

Reasonably as we would think so,

> It is easy for Engineers to "assume or trust" that the rail offset were to be maintained within the "flaw limit" by someone else so and so such as Fabricators

There is a reasonable thinking that might work "creatively" if only when the "not yet delivered girder" is still lying flat on the desktop screen, drawing board or in print, etc., but the biggest problem is, no one is questioning how and who is to (1) keep the "flaw" under limit or to (2) check if the "flaw" is exceeded the limit at some point in time yet to come during active service into forever and ever;

> So intuitively out of good intention to allow a little amount of rail offset, what being described there is as if in equivalence, we are awarding a not-so-perfect driver a license with a conditional statement: "It's **OK** to ride with a little zigzag at your own pace provided that no one goes over the speed limit or hits someone" or even if so but as long as no one catches it, is that really **OK**?

OK only on the surface, because keeping the allowed "flaw" under limit is a sneaky way to cheat the system during design time or when no load was applied yet. To find out if anyone could insinuate from such good intention as to how to protect the **CRG** from experiencing excessive "offset under load" against the "norm" then, all Engineers should do some regulating on their own, or in a way on our own or on your own, but how?

For example, to a 30 ^{ft} member under the current design Standard as of this writing, **AISC** would tolerate an imperfection **e** = 0.375" while **AIST** would only allow **e** = 0.15" and the difference could be very significant or if expressed by simple ratio between the two, here we have:

> $\mathbf{Sweep_{\_AISC}} = 2.5 * \mathbf{Sweep_{\_AIST}}$

Referring back to **Example 6.1**:

> The resulting warping normal stress, if based on $\mathbf{Sweep_{\_AIST}}$, is at best 7.5% (= 0.5 * **e** = 0.5 * 0.15") of the flexural bending stress based on calculation using approach 2 (or about 13% per approach 1)

> And then the percentage would grow accordingly by 2.5 times for **Sweep$_{AISC}$** that would give a very frightening 32.5% per approach 1− see how threatening it is to the girder when using **Flexure Analogy**

It is common that the as-built structural configuration was acceptable from limiting the amount of “sweep” point of view, and be given a passing grade per acceptance of post-construction (as-built) alignment survey result to start with. But, here is the bad news; there is always a vicious circle looming:

> *The passing grade be it given shortly after the construction does not offer any guarantee that the structure would always be free from the effects of more pronounced imperfection later on after the structure is subjected to loads*

And rightfully so, here are some of the most misleading notions in **CRG** design:

- Assuming the influence from the tiny amount of Code-blessed allowable “sweep” is negligible when the **CRG** is newly installed and

- Assuming that such blessed condition could last forever solely based on Engineer’s wishful thinking

As matter of fact, the imperfection came from other yet-to-show-up sources together with the initial fabrication-sourced “sweep” can easily add up to a very substantial amount once the **CRG** is placed in service for a lengthy period of time, or among the worst of all even <u>in no time</u> prior to the official startup of the facility

> *And based on detailed close-up inspections, there is no teasing on the matter as it did happen in real life that some of the brand new facilities didn’t survive the initial alignment check even before the grand opening ceremony took place*

What does that tell us?

By measuring against any norm at any moment in time − then or now, before or after either progressively or unexpectedly − imperfection could always grow (or shrink if luckily but rarely) so is the passing grade could become a flunking status or vice versa

> By then, perhaps no one is interested in what **AISC** or **AIST** said or didn’t say

Up to this point, the focus was on the “sweep” originated from structural fabrication only, but there are mechanisms from other non-structural implications that can throw us off course in a jiffy or in the long haul, or simply that there were too many ways and means for a **CRG** to get “swept” off further than the innate “sweep”

To name a few:

- Had anyone considered that “sweep” and other restrictions (or allowances) also apply to the rail per **CMAA 70** on top of the structural-based sweep, would that be a double whammy to the structure that has to endure the punishment from the combination of two forms of sweep?

- Building column could be off from its own vertical centerline, although within the permissible tolerance on its own behalf, but the horizontal projection from the column tilt would be additive to the original (initial) girder sweep, then what?

- The local structural framing component(s) could be out of square due to local or global flexibility issue – affecting many elements under the roof and above the roof such as excessive snow built-up – or otherwise there is possibility the charging crane could be constantly loaded lopsidedly and/or the crane framing itself could be severely out of square in the first place

- Certain portion of the crane bay/aisle was always under intense heat that may cause uneven expansion-contraction issue or (mild) rail snaking

- Girder was too flexible against lateral movement to begin with. It always suffers considerable tilt under flexure and/or torsion inducing either temporary or permanent twisting or warping imperfection. The situation is more pronounced when girder was not properly design against excessive deflection, especially those having unsymmetrical sectioned profile

  In this regard, the engineers should ask ourselves honestly how often have anyone seriously calculated the deflection of the girder

- Foundation pad might be unevenly settled, heaved or rotated, etc.

After all, the realistic world that a **CRG** is living in could be many times more "imperfect" than we Engineers have ever thought of

On and on, and suddenly it becomes much more complex to quantify the true imperfection being so out-of-the-norm and so much more than the Code-allowed sweep if unchecked – thus if not confirmed by a timely or more frequent survey or monitoring by more proactive measures then we'll be cheating ourselves (and **CRGs**) using just a marginal tad of imperfection and got away with it, aren't we?

As if it wasn't confusing enough, now consider the real life situation that sometimes the survey data collection was focusing on the crane rail at first, but then got tangled up with the column offset, building shifting, girder sweep with the independent rail offset reading together without clarifying which baselines or work points/lines were chosen and how they were setup and/or interpreted, etc. In summary:

> The fact is, anyone – Engineers, Inspectors, Surveyors, etc. – have equal chance to make a small mistake or big mistake. The mistake could be all started out as a data quantity issue but ended up with a methodology or data quality issue

For that reason, it could be more wrong and more dangerous to trust or even dare to assign an <u>unjustified</u> rule of thumb in the allowable rail alignment tolerance by a Structural Engineer for structural design consumption without considering if the allowed or restricted amount of "imperfection" set by "us" is truly harmful or beneficial to the structure, or is it to the rail or to the crane, or to all entities when all is said and done

Now shift gear <u>on the loading side</u>:

Perhaps, the perfection out of zero-**X**-moment arm could have been achievable for symmetrical section members subjected to influence of application of <u>pure vertical load</u> $\mathbf{P_y}$ alone at the beginning – with zero **P-δ** – but the short-lived zero moment arm would be immediately cultivated to something else as soon as:

- $\mathbf{P_x}$ load joining the action and

- The dealing of **CRG** of unsymmetrical section under any load conditions in any case with or without $\mathbf{P_x}$ influence <u>*even under its own dead load*</u>

Obviously, to the inspectors seeing strange happenings on site, No one should endorse an immediate teardown or write up an "unacceptable" comment to every occasion when condition deviates from the norm – only if we all agree to a universal norm – in each and every operating facility. The problem is, no inspector knows what amount of deviation is too excessive or moderate, and that is not up to them to know to carry out their responsibility. No sweep or too much sweep is not a direct engineering contract issue; inspectors should just document the fact and let other parties to handle the rest

However, engineers must deal with imperfections beyond simple Code-sponsored "sweep" by specifying a reasonable runway rail float or runway misalignment as a genuine design condition in addition to the normal "**Runway Loading Input Specification**."

6.13 Runway Design Rail Float (Rail Misalignment) Specification

On the surface or for the sake of discussion, this is a debatable subject to some as it would be and should be, but as we have come this far, what is the point of debating?

For design engineering consumption, most of us if not all are at lost in this regard; because, to this day as of this writing, there is no **CRG-associated** Code or Design Guide had taken the lead to put forward a criterion for practical use

Anyhow, perhaps a good subject for debating, provide we place focus only on how should the dynamic float and the static misalignment be brought together for **CRG** design consideration; but arguing is useless, to come up with a reasonable figure such that it works out in protecting both the structural and the mechanical components should be the primary objective

Survey results of rail misalignment collected in the recent past revealed that the deviation from norm routinely exceeds 0.125% of the member length on average, which translates into a more technical term of **L** / 800 or 0.00125 * **L** or **0.03"/ft**. This value seemed too high already, not to mention that some other sets of survey result were even worse, much higher than both the **AISC** and **AIST** limits on fabrication tolerance we should say.

One wonders:

First of all, how come not one of those pro **CMAA 70** standard practice promoters was screaming at that yet? Secondly, by applying 0.125% offset to **Example 6.1 …………..**, the value of "**e**" could have been 0.45", and the warping normal stress would have grown to an astonishing **22.5% of the flexural bending stress** per approach 2 – and that is way beyond negligible, isn't it?

Important to know:

The main purpose of making stress calculation as given in **Examples 6.x** was to establish that nonlinear structural response to torsion does exist in a very big way; and we should not ignore the "hidden" impact on a girder's vulnerability to such incidence once we know it's there.

The objective of what demonstrated through **Examples 6.x** should be straightforward to follow, but, notice that the load case exploited in those calculation was based on a much simplified design model, thereby it's not quite adequate for actual application because it missed a whole lot more – compared to the real thing

So to prove a point intentionally, the **Examples 6.x** procedure covered "vaguely" the influence from rail offset due to static version of misalignment only, which is based on applying the $\mathbf{P_y}$ vertical load onto a "single wheel" only

Visualize what it would take to make serious calculation given an impossible setting; what happens if we (1) let in multiple wheels to join in the action, and meanwhile (2) try accounting for the rail offset effects engaging the dynamic nature of $\mathbf{P_x}$?

By all means it would develop from a "± **P-δ**" incident at start and then lead in the way into a very complex "± **M-θ**" mess, all because:

- The quantity of bona fide **δ** is actually a sum (combination) of the direct $\boldsymbol{\delta_x}$ from flexure and the straight **X**-projection due to rotation $\boldsymbol{\theta_z}$ attributed to the accompanied torsion
- It is a nonlinear event as proven, the complication adds up immediately if considering $\mathbf{P_x}$ being applied in reversible sense about the **shear center**

One can only imagine the immense amount of effort needed to solve non-linear deflection problem involving multiple wheels, i.e. doing the real thing is a very different thing

> Trying to establish a custom numerical process that can grind its way out of the iteration progression as to figuring out at which point the calculation could (numerically) converge would be quite a chore, perhaps an impossible chore to accomplish
>
> So let alone getting good handles on what the *final stress* and the *final deflection* would attain upon convergence. Also don't forget, it is for a full-blown multi-wheel moving load situation

Consider even a much worse situation, think about what it takes counting the extra overhead needed if given unsymmetrical sectioned member meeting fatigue design mandate

---

From all indications, it turns out quite clear that, using pure static rail misalignment taken straight from a survey is not enough for good reason.

To minimize further confusion, we should and could settle and develop a unified rail-float definition that treats every technical or non-technical matters and terms on equal basis as if all are participating in the so-called "**girder design rail float**" event.

Nevertheless, before being driven into the development too soon we should take note of a couple of facts:

> Considering the dynamic nature ingrained in a moving wheel load situation:
>
> The maximum rail float, in reality, does not come about uniformly along the full length of the girder; the peak value of rail offset may occur at one of the load point(s) or anywhere in between that were not necessarily situated at the mid-span – imagine the state of affairs as complex and dynamic as if fixing the result of a tug-of-war battling between flexure and torsion − which would attenuate instinctively and should vanish near or at the supports, in theory

Think visibly at this point, it might be unfair to the **CRG** by imposing it a generic **constant** rail float to the entire girder from end to end, but it would definitely be conservative to do so for sure.

> And then whether as lead-in or lead off on the subject of being too conservative or not conservative enough, there might be other better tactics or ideas showing the way how to tie down a reasonable rail float value for design
>
> But, unless there is a better resolution, we could only narrow down to two reasonable approaches (of two extremes) in handling the situation:

- Establishing the rail float − *the hardest way to make it sound easy if achievable and only if it's worth the effort* − as a **nonlinear function** with numerical peaks and valleys (or so-called floats) varying along the girder length performed by a nonlinear analysis by someone using similar approach as demonstrated in the **preceding Examples**, or

- *Going by the easiest route*; simply using a constant magnitude of "float" to be applicable uniformly from end to end and call it good

Yet for general purposes, one may use a qualitative expression, as shown below, by omitting the "rail" clause in respective term:

± Design girder float = Misalignment ± Slip ± Offset

It is plain to see that the ± sign is meant for those entities of dynamic nature and the one(s) without a sign is for steady-stated static condition

Most of us could have agreed at this point that − in numerical sense − anything being dynamic may be too uncontrollable while that being static is more amiable to reality and/or certainty.

Rail slippage has a very narrow range depending on what type of rail clips/fasteners were used granting "slippage" sounds more dynamic and unstable in nature. Misalignment although is static but that only represents an instantaneous quantity highly dependent on when the measurement was taken, even the upper bound of it may or may not change over time

Among all probable (geometry and loading) causes, "floats" and "slips" due to $\mathbf{P_x}$ **and** $\mathbf{P_y}$ should be the most dynamic parameters affecting crane rail's "sidesway movement" that may sway one way or the other

Except for as measured misalignment, the quantity of every other cause (term) appeared so fuzzy; it becomes impossible to define numerically what the true "float" really is. But instead of rendering the forgoing expression for ± float to be meaningless, we may consider simplifying the task − without worrying what's dynamic and what's static − into:

± Design girder float = ± $\mathbf{k_f}$ *** Misalignment**

In the above expression, $\mathbf{k_f}$ could be any practical quantity, which has to be progressively finalized from a pseudo-nonlinear analysis involving a full-blown torsional treatment through future **R&D** effort. But for practical purpose in the interim:

If and only if the **Misalignment** *of **L / 800** is an accepted reasonable measure from most survey results then using an initial* $\mathbf{k_f}$ *= 2 leading to the specification of ± **L / 400** as a design float should be a good starting point*

Authors' Opinion:

Using a token value ± **L** / **400** – or any reasonable value – for design does not insinuate that a typical **CRG** is really going to deflect laterally by that amount, nor the rail is really in big trouble.

The purpose of using a somewhat fictitious misalignment ± **L** / **400** for design consideration is to **make the girder torsionally stronger** through vastly simplified progression, thereby less prone to having serviceability issue later on. But on the other hand if we don't buy it then we may end up with a much more flexible girder (in torsional sense) that may actually deflect laterally in more substantial amount than anticipated if not **L** / **400**, Believe it or not, some of the worst misalignment survey results on records had registered to a whopping ratio of **L / 300**. At those rates, Readers can make up a picture of what the girder (flange) looked like and what had happened to the crane rail.

What is also implied here?

The girder design, in lieu of using a reasonable $\mathbf{k_f}$ factor, is a trial and error process that one should not walk away from the **CRG** and call it done after only one singular analytical session. The process of structural qualification should be progressively justified.

After all, the key is accepting the base amount of **Misalignment** from treating k_f as a modifier, sort of buying/paying for an engineering life insurance. We can bring out a good real-life situation to convince those die-hard naysayers why using $k_f = 2.0$ (or ± **L** / **400**) is not an overkill.

The Readers can calculate the $\mathbf{k_f}$ *value on their own for an* ***extremely out-of-whack*** *girder of 112*^{ft} *long with an officially documented permanent offset of 5" measured at the top flange*. Beyond literal meaning, permanent offset has a subtle warning to engineers; the girder might be living in a plastic world.

6.14 Applied Torsional Moment $\mathbf{M_z}$ ($\mathbf{M_t}$)

It is well understood, at any given wheel load position, the engineering focus is not only on the vertical load $\mathbf{P_y}$ (for it always presents) but also its on-and-off derivatives, the lateral load $\mathbf{P_x}$. Together they both contribute to the unavoidable torsional moment $\mathbf{M_z}$ – although a no-big-deal happening on the surface, but how it racks up the racking power behind the scene is a rather intricate matter.

At great disadvantage and at first hand, **CRG** knows – better than we do – of what and where it hurts the most and how bad it feels from the tug-of-war contest between $\mathbf{P_y}$ and $\mathbf{P_x}$; besides that, it tallies up the cycles – more accurately than we could – of the occurrences whenever there is any thrashing discomfort induced by tensile stress fluctuation or shear stress reversal.

CRG can pin point exactly at any node in **3D** whether it experienced minor deterioration or something more severe than natural wear and tear (fatigue, for example) when the stress is high enough and the cycle count is up. Yet, how to quantify the load cycle events based on a design against fatigue point of view could be contentious once we start counting. Does that make any good sense or no sense is anybody's call; but it sure can stir up some interest from an "unexaggerated" scenario set out as follow:

When the leading wheel made its entry into the girder span carrying only vertical $\mathbf{P_y}$, action begins

- Same wheel with lateral load $\mathbf{P_x}$ join in
- Same lateral load $\mathbf{P_x}$ acts in reverse
- Lateral load $\mathbf{P_x}$ stops
- Lateral load $\mathbf{P_x}$ reactivated
- Lateral load $\mathbf{P_x}$ acts in reverse again
- Lateral load $\mathbf{P_x}$ stops again
- ……
- Before long second wheel made its way in
- Third wheel joins in
- Then forth wheel
- ……
- First wheel leaves the girder span
- ……

What illustrated is not an "exaggerated" drama but scenarios repeating over and over in real life. Before or after the overhead crane was driven away, it would have left behind so many cycles of goings-on that needed be tallied "fairly" to facilitate proper fatigue assessment. Predictably there might be numerous ideas on what number of cycles to keep track of and what not.

How many cycles, give and take, isn't the problem just yet; the real concern is the effects from fluctuation of torsion that came with it that sometimes Engineers do not see or don't want to see.

$\mathbf{M_z}$, by general definition, is the "externally applied" rotational moment about a longitudinal axis that is parallel to the **Z** direction, yet more specifically, once again, the **Z**-axis of **CRG** torsion interest must pass through not the **elastic centroid** but the **shear center**.

On occasions the notation $\mathbf{M_z}$ is used to represent exclusively the internal torque at equilibrium, therefore in order to tell them apart from the externally applied torque in that case was designated as $\mathbf{M_t}$ − it doesn't make much or any difference for the purpose herein.

To weed out the likelihood of garbage-in-garbage-out situation, now should be the "best chance" to have the **shear center** coordinates in check, then after confirmation if further letting:

> $\mathbf{e_y}$ = Y-projection of the distance measured from the rail base to the **shear center**
> $\mathbf{d_r}$ = Nominal rail depth
> $\mathbf{e_x}$ = X-projection of the distance from rail base to the **shear center**, and
> $\boldsymbol{\delta_{GL}}$ = Design girder float (along the lateral X-direction) such as **L** / 600, **L** / 400, etc.

And if considering (1) the numerical sign carried by both $\mathbf{P_x}$ and $\boldsymbol{\delta_{GL}}$ could be **independently** made reversible and (2) the <u>in phase and/or out of phase</u> situations along **X**-direction then the magnitude of $\mathbf{M_z}$ may be simplified as:

$$\pm \mathbf{P_x} * (\mathbf{e_y} + \mathbf{d_r}) + \mathbf{P_y} * (\mathbf{e_x} \pm \boldsymbol{\delta_{GL}})$$

That in turn could be augmented in full-blown expression into the following four cases:

$$Mz_1 = + c_x * P_x * (e_y + d_r) + c_y * P_y * (e_x + \delta_{GL})$$
$$Mz_2 = - c_x * P_x * (e_y + d_r) + c_y * P_y * (e_x + \delta_{GL})$$
$$Mz_3 = + c_x * P_x * (e_y + d_r) + c_y * P_y * (e_x - \delta_{GL})$$
$$Mz_4 = - c_x * P_x * (e_y + d_r) + c_y * P_y * (e_x - \delta_{GL})$$

Not to be forgotten in which the additional parameters, $\mathbf{c_x}$ and $\mathbf{c_y}$, are the load combination factors applicable to $\mathbf{P_x}$ and $\mathbf{P_y}$ loads, respectively, as defined in <u>Task #3</u> under the "**Runway Loading Input Specification**."

More specifically for a few practical examples, $\mathbf{c_x}$ <u>may or may not be</u> 0.5 when considering fatigue while $\mathbf{c_y}$ <u>may or may not be</u> 1.25 for single crane impact, or 1.0 for multiple crane application, all depending on what type of crane is in use and which Project Design Standard is governing, etc. In order not to miss anything important, the four cases exemplified herein should be applied as an all-inclusive group for each load combination case as required.